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ABSTRACT

Derivation of Soil Screening Guidelines for Gross Alpha/Beta Radioactivity for United States Air Force Deployment Sites

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The US Air Force (USAF) has created radiation dose levels to indicate how much environmental exposure to ionizing radiation is necessary to warrant further individual dose investigation as well as decide what medical surveillance is necessary. However, gross alpha and beta screening limits for radionuclides in soil that would coincide with these dose levels have not been developed.

USACHPPM (United States Army Center for Health Promotion and Preventive Medicine) has received soil samples from worldwide locations to be analyzed for radiation safety purposes. The concentrations of radionuclides in these soils can be used to estimate the dose so that further health assessments can be made.

A dose rate can be related to the concentration of specific radionuclides in soil by using the computer program RESRAD. These soil concentrations can be related to gross alpha and beta limits based on their individual decay emissions.

The objective of this study is to develop gross alpha and beta screening levels that, if exceeded, indicate a potential dose to deployed Airmen that is above a specified total dose limit. The results of this study are to be used to analyze isolated areas or small batches of samples.

Derivation of Soil Screening Guidelines for Gross Alpha/Beta Radioactivity for

United States Air Force Deployment Sites

by

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Biomedical Science Corps, US Air Force

Thesis submitted to the Faculty of the
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Dedication

This work is dedicated to my mother and father, Anne Livingston and Rev. Dr. William Livingston, whose guidance, support, and care made this degree possible.

“God is our refuge and strength, an ever-present help in trouble”

Psalm 46:1

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I. Background

The US Air Force has created dose levels (US Air Force, 2001) to indicate how much environmental exposure to ionizing radiation is necessary to warrant further individual dose investigation as well as decide what medical surveillance is necessary. However, gross alpha and beta screening limits for radionuclides in soil that would coincide with this dose limit have not been developed. At this time, a limit of 20 pCi/g alpha and beta are used as an estimated limit, although this is somewhat arbitrary (Beegle, 2007).

USACHPPM (United States Army Center for Health Promotion and Preventive Medicine) has received soil samples from worldwide locations to be analyzed for radiation safety purposes as part of a deployment occupational and environmental health program. Two analyses are performed on these samples: gamma spectroscopy to identify individual radionuclides and proportional counting to measure a gross alpha and beta emission rate in the soil. The concentrations of radionuclides in these soils can be used to estimate the dose so that further health assessments can be made. They can be used to estimate the natural background and industrial contamination from medical and reactor use such that correct interventions can be performed to protect military personnel, the public, and others.

In 2001, there was an attempt to quantify an acceptable concentration of alpha particle activity and beta particle activity in soil at deployment locations. This study considered several factors unique to deployment exposure. First, it recognized that other models are based on lifelong exposure, while deployment

settings should be considered temporary (usually about 6 months). Also, deployed populations usually do not sustain themselves with food and water from the local environment. This is an important consideration when assessing potential exposure pathways.

However, this study was not published for several reasons. First, it did not include enough details and references regarding inhalation rates, ingestion rates, and concentrations of natural radionuclides. Second, the calculations did not include measurements of several radionuclides that are of military significance. It only accounted for rubidium-87, potassium-40, the Uranium Series and the Thorium Series, which are all natural radionuclides. This did not include radionuclides used in medical procedures such as cobalt-60 and iridium-192, or reactor products, such as cesium-137 or the neptunium series.

The objective of this study was to develop gross alpha and beta screening levels that, if exceeded, indicated a potential dose to deployed Airmen that was above a specified total dose limit. Since there are several dose limits that can be specified based on who is being protected, several dose limits were considered for this study.

The results of this study are to be used as screening levels with deployment occupational and environmental health samples. If the alpha/beta emissions in the soil are below the gross alpha and beta numbers determined in this study, the site can then be considered suitable for a deployment based on radiological concerns. If the alpha/beta emissions in the soil are above the gross

alpha and beta numbers determined in this study, further considerations and investigations should then be performed that are outside the scope of this study.

II. Literature Review

A. Dose Assessment and Dose Limits

1. Air Force Instruction 48-148

Air Force Instruction (AFI) 48-148: “Ionizing Radiation Protection” (US Air Force, 2001) presents dose guidelines based on the International Atomic Energy Agency (IAEA) Safety Series 115. The AFI 48-148 guidelines are a set of recommended interventions to use if a population is exposed significantly. For a total effective dose equivalent less than 0.05 rem during a mission, no intervention is necessary. Some actions necessary based on exposure are to begin recording individual doses and to limit tasks performed in that area to only ones seen as essential.

Also provided are instructions for what dose will be averted by sheltering and evacuating by using a dose called a Generic Intervention Level (GIL). These levels are provided to assist in making decisions in case of a large accident. Assessment can be made based on what health effects can be avoided and which are inevitable.

This instruction also provides surface contamination levels that are acceptable for an Air Force mission. This contamination is measured in terms of disintegrations per minute per square centimeters. Guidance is given as a maximum contamination as well as a maximum for contamination that is removable from that surface. It also provides contamination limits from equipment and protective clothing for 7-day operations and for 3-month operations.

2. STANAG 2473

The North Atlantic Treaty Organization (NATO) published Standard Agreement 2473 in 2004 (North Atlantic Treaty Organization, 2004). This agreement was made to provide guidelines for radiation protection during non-Article 5 crisis response operations (CRO). Article 5 in the NATO treaty refers to armed attacks against one or more of the nations in NATO, so this STANAG refers to operations not responding to such attacks.

This document creates a standardized methodology for assessing the dangers of risks and making appropriate decisions based on this data. It puts emphasis on blocking off areas with dose rates over 0.0002 cGy (0.2 mrad) per hour to disallow entry to any non-essential personnel.

This document defines Radiation Exposure States (RES) and gives recommended actions for these dose categorizations. No individual monitoring is recommended for RES Category 0, which relates to doses up to 0.05 cGy (50 mrad). Doses above 50 mrad require such actions as recording individual dose readings, performing dose control measures, and limiting tasks to critical only.

3. ICRP Report 26

International Commission on Radiological Protection (ICRP) Report 26: “Recommendations of the International Commission on Radiological Protection”, defines the basic concepts used in measuring ionizing radiation. The principles defined here, written in 1977, are the basis for US Title 10, Code of Federal Regulations, Part 20 (10 CFR 20).

The absorbed dose is defined to be the amount of energy absorbed in a material per unit mass. Dose equivalent (H) is defined to be the absorbed dose (D) multiplied by a quality factor (Q) for the type of radiation (International Commission on Radiation Protection, 1977).

$$H = DQ \tag{1}$$

The units for dose equivalent are sieverts (Sv). One sievert is equal to one joule of energy per one kilogram (also equals 0.01 rem). Table 1 shows the values ICRP 26 defines for the quality factor (International Commission on Radiation Protection, 1977).

Table 1: Quality Factors (Q)

Radiation Type	Q
X, gamma, beta	1
Neutrons, protons and singly-charged particles of rest mass greater than one atomic mass unite of unknown energy	10
Alpha particles and multiply-charged particles (and particles of unknown charge), of unknown energy	20

The ICRP uses another weighing factor, w_T, to represent the proportion of the stochastic risk resulting from a specific tissue (T) to the total risk if the entire body is irradiated uniformly (International Commission on Radiation Protection, 1977). The ICRP created a condition for modifying the dose based on tissues affected to compare to the annual dose limit.

$$\sum_T w_T H_T \le H_{wb,L} \tag{2}$$

H_T is the annual dose equivalent to tissue T. The annual whole body dose equivalent ($H_{wb,L}$) recommended by ICRP 26 is 50 mSV (5 rem). The tissue weighing factors are shown in Table 2 (International Commission on Radiation Protection, 1977).

Table 2: Tissue Weighing Factors (W_T)

Tissue or Organ	W_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surface	0.03
Remainder	0.30

ICRP Report 60: "The 1990 Recommendations of the International Commission on Radiological Protection" is an update on guidance of the fundamental principles and quantities used in radiation protection that hadn't been updated since ICRP Report 26, which was published in 1977. ICRP Report 60 recommends a new effective dose limit for occupational exposures. This limit is 0.1 Sv (10 rem) during a five-year period and 0.05 Sv (5 rem) during a single year. During a five year period, the average annual dose cannot exceed 0.02 Sv (2 rem) (International Commission on Radiation Protection, 1990). Although these are the ICRP's most updated recommendations on dose limits and weighing factors, the US Nuclear Regulatory Commission (NRC) and the US Environmental Protection Agency (EPA) still operate based on the recommendations of ICRP 26 and 30.

4. RESRAD

RESRAD is a computer program designed to evaluate the total effective dose equivalent (or TEDE) to an average occupant of an area based on the residual radioactive concentration in the area's soil (Yu et al., 2001). It was developed at Argonne Laboratories under the sponsorship of the Department of Energy. The first version was released in 1993; the latest version (RESRAD 6.3) was completed in 2005. This program has been regularly used in numerous organizations for developing policy, including the EPA and the IAEA.

When calculating a total exposure, there are nine pathways considered: direct (external) exposure, dust inhalation, radon inhalation, soil ingestion, meat ingestion, plant food ingestion, aquatic food ingestion, milk ingestion, and water ingestion.

These pathways fall into two broad categories: water-dependent and water-independent. The water-independent pathways include external exposure, dust inhalation, radon inhalation, soil ingestion, meat ingestion, plant food ingestion, and milk ingestion. The water-dependent pathways include radon inhalation, meat ingestion, plant food ingestion, aquatic food ingestion, milk ingestion, and water ingestion. Some of the pathways have components in both categories, since meat, milk, and plant food contain both water and dust from the environment.

The calculations in RESRAD code do not assume the radioactive concentrations in the soil are constant over time. Based on erosion rates and the presence of very short-lived radionuclides, the dose rate can change. For this

purpose, the results of the dose calculations are given as a rate in units of millirems per year. The summary output presents these rates individually from each pathway (ingestion, inhalation, etc.), each individual radionuclide, and as a total from all sources.

Argonne National Laboratory has released several documents in conjunction with RESRAD explaining methodology and logic used to build the program. One document, titled “External Exposure Model Used in the RESRAD Code for Various Geometries of Contaminated Soil” (Kamboj, Yu, & Poire, 1998) explains what mathematical models they used to create Dose Conversion Factors (DCF) for external radiation to relate soil concentrations to dose rates.

The EPA’s Federal Guidance Report, Volume 12 (FGR12) dose coefficients are used to create these DCFs (Eckerman & Ryman, 1993). However, since the FGR12 coefficients are only defined for four different soil depths (1 cm, 5 cm, 15 cm, and infinite), RESRAD’s programmers had to create a method for interpolating information on all other depths. This was done by creating a depth factor, which is a ratio of dose at a given depth to the dose at an infinite depth. This depth factor is then stated as a function of depth using fitted parameters and the following equation:

$$F_D = \frac{DCF(T_s = t_s)}{DCF(T_s = \infty)} = 1 - Ae^{-K_A \rho t_s} - Be^{-K_B \rho t_s} \tag{3}$$

F_D is the depth factor and t_s is the depth of the contaminated soil. There are four “fit parameters” (A, B, K_A, and K_B) that are calculated using FGR12

DCFs. All of these parameters have to be positive and it is necessary for A+B=1. As the thickness of the soil approaches zero, the DCF should approach the FGR12 values of dose coefficients for exposure to contaminated ground surface. A soil density (ρ) of 1600 kg/m^3 is used.

Once the fit parameters were calculated, the coefficient (now referred to as the “fitted DCF”) was calculated at 1 cm, 5 cm, 15 cm, and infinite depths to get a comparison of how the fitted DCFs compare with the FGR12 DCFs. All of the fitted DCFs are within 10% of the FGR12 values.

RESRAD’s calculation of dose is performed by calculating a dose/source concentration ratio (denoted by $DSR_{ip}(t)$). Equation 4 considers eight of the nine exposure pathways (radon inhalation is a separate equation).

$$DSR_{ip}(t) = \sum_j DCF_{j,x(p)} \times BRF_{i,j} \times \sum_j \int_t^{t+t_{\text{int}}} ETF_{ij,pq}(\tau) \times SF'_{ij,pq}(\tau)\, d\tau \tag{4}$$

Exposure pathways are designated by 3 parameters in Equation 4: *p*, *q*, and *x(p)*. How these labels are applied is shown in Table 3.

Table 3: Index Labels for Exposure Pathways

Exposure Pathway	*X(p)*	*p*	*q* (ranges)
External	1	1	1
dust inhalation	2	2	1
plant food ingestion	3	3	1, 2, 3, or 4
meat ingestion	3	4	1, 2, 3, 4, 5, or 6
milk ingestion	3	5	1, 2, 3, 4, 5, or 6
aquatic food ingestion	3	6	1
water ingestion	3	7	1
soil ingestion	3	8	1
radon inhalation*	2	9	N/A

*Radon inhalation is not considered in Equation 4 and does not use the q parameter.

The index labels *i* and *j* represent the separate radionuclides involved in the calculation, where *i* refers to initially existing radionuclides and *j* refers to radionuclides in its decay chain. The $BRF_{i,j}$ is the branching factor. This dimensionless factor is the fraction of the total decay of radionuclide *i* that results in the growth of radionuclide *j*.

The $DCF_{j,x(p)}$ is the dose conversion factors for the individual pathways, which are described above. t_{int} is the exposure duration. This duration can be a maximum of one year.

The factor $ETF_{ij,pq}(t)$ is the environmental transport factor, which is dimensionless for the external radiation pathway but has units of g/y for every other pathway (since the DCF has units mrem/y per pCi/g for external and mrem/pCi for ingestion and inhalation, the ETF makes all of the units the same for each pathway). The ETF is a function of different parameters for each of the three major types of exposure (external, inhalation, and ingestion).

For the external pathway, the ETF is a function of four dimensionless factors.

$$ETF_{i1}(t) = FO_1 \times FS_{i1}(t) \times FA_{i1}(t) \times FCD_{i1}(t) \tag{5}$$

The first is the occupancy and shielding factor (FO_1), which considers the time spent inside and the shielding between the person and the soil when they are inside. The second factor is a shape factor ($FS_{i1}(t)$), which is used to correct for a non-circular shape (a circular shape of land is typically assumed: the shape factor is equal to 1 for a disk source).

The third factor for the ETF is a radionuclide-specific area factor (FA_{i1}(t)) created by weighting energy-dependent area factors by their photon fraction and dose contributions. A energy-dependent area factor is the dose a person would receive from the considered geometry divided by the dose a person would receive with these same parameters except an infinite area. It takes into account the height from the surface to the person's midpoint (T_a), thickness (T_s), cover depth (T_c), and radius of area (R),

$$FA_{\gamma}' = \frac{D[R = r, T_a = 1m, T_c = C_d(t), T_s = T(t)]}{D[R = \infty, T_a = 1m, T_c = C_d(t), T_s = T(t)]} \tag{6}$$

The fourth factor of the ETF is the depth-to-cover factor (FCD_{i1}(t)), which is similar to the radionuclide-specific area factor except it considers thickness instead of area. The depth-to-cover factor is the DCF for the contaminated zone thickness divided by the DCF for an infinite thickness. The contaminated zone thickness takes into account initial thickness as well as the erosion rate of the cover thickness.

$$FD_{i1} = \frac{DCF_i^{FGR}[T_s = T(t)]}{DCF_i^{FGR}[Ts = \infty]} \tag{7}$$

The environmental transport factor (ETF) for dust inhalation considers the cover and depth factor (FCD_2(t)), the occupancy factor (FO_2), and the area factor (FA_2), as well as an air/soil concentration (ASR_2) ratio and the annual intake of air (FI_2).

$$ETF_{i2}(t) = ASR_2 \times FA_2 \times FCD_2(t) \times FO_2 \times FI_2 \tag{8}$$

The air/soil concentration ratio (ASR_2) is the average concentration of soil particles in the air, given in units grams per meter cubed (g/m^3) (C. Yu, 1993 #14). The annual intake of air (FI_2) is in units meters cubed per year (m3/y).

The environmental transport factor (ETF) for soil ingestion is a function of area factor (FA_8), cover and depth factor (FCD_8(t)), occupancy factor (FO_8), and the annual intake of soil (FSI).

$$ETF_{j8}(t) = FSI \times FA_8 \times FCD_8(t) \times FO_8 \tag{9}$$

The annual intake of soil (FSI) has units of grams per year.

Decay, ingrowth (the buildup of progeny), and leaching are represented by the source factor ($SF'_{ij,pq}$(t)), which is equal to one for all water-dependent pathways, since it is intertwined with the environmental transport factor. For water-independent pathways, the source factor is the ratio of concentration after a period of time (S_{ij}(t)) and the sum of the initial concentrations for each radionuclide (S_{ij}(0)).

$$SF'_{ij,pq}(t) = SF_{ij}(t) = \frac{S_{ij}(t)}{\sum_j S_{ij}(0)} \tag{10}$$

S_{ij}(t) is calculated by applying an exponential decay equation to the radionuclide in question and also adding the production of this radionuclide if its parent radionuclide is present.

B. Definitions

1. Tile 10 Code of Federal Regulations - Part 20

The NRC has set dose limits to the general public as well as separate standards for occupationally exposed workers from the use of radioactive materials under its jurisdiction. These limits are shown in the Code of Federal Regulations, specifically 10 CFR 20 (part 20 is the "Standards for Protection against Radiation).

10 CFR 20 defines several concepts in dose measurement in a "definitions" section. The effective dose equivalent (EDE) is the external dose modified by the weighing factors for radiation type and organ irradiated. The committed effective dose equivalent (denoted by CEDE or $H_{T,50}$) is the absorbed dose with both weighing factors figured in (as described in the "ICRP 60" section) and integrated over 50 year for an adult and 70 years for a child. This is a total committed dose from an internal exposure such as an inhalation or ingestion intake.

The TEDE is the sum of the EDE from external exposures and the CEDE from internal exposures. This is commonly referred to simply as the "total dose" (Nuclear Regulatory Commission, 1991).

The TEDE that an occupationally exposed individual can receive is 5 rem in a year. However, a member of the general public should not receive more than 0.1 rem in a year. In any one hour, the exposure limit is 2 mrem (Nuclear Regulatory Commission, 1991).

The limits given in 10 CFR 20 are based on the principles of ICRP Reports 26 and 30. Although ICRP Reports 60 and 61 updated the radiation and tissue weighing factors, US federal law still reflects the factors from ICRP Reports 26 and 30.

There are cases where these limits are not feasible in regards to military personnel. However, these limits are enforceable by civil authorities for exposures to off-base civilians.

2. Federal Guidance Reports 11 and 12

Federal Guidance Report 12, titled “External Exposure to Radionuclides in Air, Water, and Soil”, was published in 1993 by the EPA. This report publishes dose conversion factors for external exposures to radionuclides in air, water, and soil. It is intended to be a companion to FGR 11, which tabulates dose coefficients for ingested or inhaled radionuclides.

The DCFs for exposure to contaminated soil are calculated to four depths: 1 cm, 5 cm, 15 cm, and an infinite depth. These DCFs are given in units of sievert kilograms per becquerel seconds or (Sv/s)/(Bq/kg). This unit makes it easy to estimate an external dose by multiplying this coefficient by the activity in every unit mass of the soil (in units Bq/kg). The mass can easily be converted to the volume of the soil by dividing it by the soil density used to calculate these coefficients, which is equal to 1600 kg/m^3.

Federal Guidance Report 11, titled “Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion”, was published in 1989 by EPA. This report calculates derived air

concentrations (DACs) and Annual Limits on Intake (ALIs) for inhalation as well as ALIs for ingestion. DACs are given in units of MBq/m^3 and ALIs are given in units of MBq.

Also presented are DCFs for ingestion and inhalation presented in units Sv/Bq. Like the FGR 12 dose coefficients, these DCFs are given for dose to 7 different organs as well as an effective dose to the entire body.

FGR 11 and 12 use weighing factors and definitions from ICRP Reports 26 and 30, which have different weighting factors and terminology than ICRP Reports 60 and 61.

C. Human Exposure Pathway Modeling

1. EPA Exposure Factors Handbook

The Exposure Factors Handbook was first published by the EPA in 1989 and has been updated since. This handbook collects statistical data relating to risk assessment of various health-related hazards.

This handbook provides EPA guidance on soil ingestion rates. Based on a study by J.K. Hawley in 1985 (Environmental Protection Agency, 1997), the rate for outdoor activities is 480 mg/day. This ingestion of house dust for indoor activities rages from 0.56 to 110 mg/day.

Based on three studies, the EPA determined the adult rate of soil ingestion to be 50 mg/day for industrial settings and 100 mg/day for residential and agricultural settings. However, due to the small number of studies, this recommendation is given with low confidence.

This handbook offers a brief review of studies and recommendations for inhalation rates. The EPA recommends three different levels of outdoor activity: light, moderate, and heavy. The inhalation rates for an average adult are 1.1 m^3/hr, 1.5 m^3/hr, and 2.5 m^3/hr, respectively. The average for an outdoor worker is 1.3 m^3/hr.

Averaged results from five studies give general rates for five levels of activity: rest, sedentary, light, moderate, and heavy. These averaged rates are 0.4 m^3/hr, 0.5 m^3/hr, 1.0 m^3/hr, 1.6 m^3/hr, and 3.2 m^3/hr, respectively.

All of the above rates are defined to be for short-term exposures only. For long term exposures, the average inhalation rate is 11.3 m^3/day for females and 15.2 m^3/day for males. Inhalation rates are more frequently studied, so these recommendations are given with high confidence.

2. ICRP Reports 66 & 89

ICRP 66: "Human Respiratory Tract Model for Radiological Protection" gives definitions for different inhalation rates, such as light exercise and heavy exercise. Light exercise is defined as "one-third of highest work load completed" (International Commission on Radiation Protection, 1995), which corresponds to housecleaning, painting, woodworking, and laboratory work. Heavy exercise is defined as two-thirds of the maximum work potential, and includes work by firemen, construction workers, farm workers, and athletes. Heavy exercise is for periods no longer than 2 hours a day.

ICRP 89: "Basic Anatomical and Physiological Data for Use in Radiological Protection" gives average breathing rates for four levels of activity:

sleeping (0.45 m^3/h), sitting awake (0.54 m^3/h), light exercise (1.5 m^3/h), and heavy exercise (3.0 m^3/h) (International Commission on Radiation Protection, 2003). These are the values given for males, which are slightly higher than the female rates.

ICRP 89 also includes estimations for time budgets. Adult males spend an average 8.5 hours asleep and 7 hours awake at home per day. They spend 2 hours a day outside (for any purpose) and 6.5 hours a day working inside. This publication makes assumptions about what they are doing during this time: the indoor time (excluding the sleep) involves one-third sitting and two-thirds light exercise. The outdoor time involves one-half sitting, three-eight light exercise, and one-eight heavy exercise. By combining these time budgets with the above breathing rates, the calculated male inhalation rate is 22.2 m^3 a day.

3. Radiological Assessment: A Textbook on Environmental Dose Assessment

The Radiological Assessment (Nuclear Regulatory Commission, 1983) text was published by the NRC to summarize several common models used to assess radionuclide movement in the environment.

This text gathers data from ICRP reports (primarily 2 and 23) relating to their concept of a “reference man.” This data is used to represent an average individual in European or American populations. The reference man is 20 to 30 years old, 170 cm (about 5 feet 6 inches) tall, and weighs 70 kg (about 155 lbs.).

Also summarized are inhalation rates from ICRP 23. This document assumes 8 hours a day of light working activity, 8 hours a day of non-occupational activity, and 8 hours a day of rest. The first two periods each have

an 8-hour inhalation amount of 9600 L (9.6 m^3) of air for men and 9100 L (9.1 m^3) for women. During the 8 hours of rest, men inhale 3600 L (3.6 m^3) while women inhale 2900 L (2.9 m^3).

III. Methodology

There are a few parameters in RESRAD that need to be examined based on this exposure scenario. First and foremost, the pathways through which Airmen can be exposed to ionizing radiation were determined. Then, the inhalation rate, ingestion rate, and time spent indoors and outdoors for Airmen are determined below.

Before gross alpha/beta results are discussed, standards are derived below for 13 radionuclides typically measured for at USACHPPM. Following that is a derivation of a standard equation relating gross alpha/beta counts to a dose rate limit.

A. Pathway Considerations

This study considers the exposure to Airmen from radionuclides in soil. In the RESRAD program, there are nine pathways by which deployed personnel can be exposed to contaminated soil. Deployed Airmen are directed by Air Force Instructions not to consume food or drink water from the land they are deployed (US Air Force, 2004), so only three pathways were considered in this analysis: external exposure, inhalation of dust, and ingestion of soil from the suspended soil attaching to food and water.

The radon pathway was neglected from consideration in this study since (1) it is expected that only isolated single or small batches of soil samples will be screened by this method and (2) indoor radon concentrations depend on many factors only one of which is the radium-226 concentration in the soil. Indoor

radon would be a consideration in a base camp assessment, which is a more advanced survey than considered in this study.

For the purpose of developing the screening levels, soil samples were considered representative of the area sampled, which was assumed to be uniformly contaminated for an infinite distance. This was a conservative assumption; if there is much less contamination off-base, this method would overestimate the dose to the Airmen. Although an infinitely contaminated area likely isn't the case, it produces a "most protective" dose estimate.

This study assumed Airmen stay on the land sampled for a majority of the deployment. The guidelines were derived on a per year basis using limits that are given in dose per year (rem/y or mrem/y). Therefore, the guidelines in this study could be applied regardless of the length of the deployment period of the Airmen. An assumption was made that all exposure conditions are constant over time.

This study was based around the activity of the Airmen with the most active physical labor and maximum time spent outdoors. The tasks considered were aerial port personnel who move cargo and baggage, which were determined via literature search and interviews to be the personnel with the highest activity rates. This was done to find a reasonably protective scenario since it will consider the maximum inhalation and ingestion rates while considering the minimum shielding from external radiation.

Therefore, the Airman considered in this study was assumed to be a male (since males have higher breathing rates) who works a 72-hour workweek. He works 12-hour shifts six days a week with no work on the seventh day. In the

typical 12-hour shift, a minimum of 10 hours are spent outside. About 6 of these hours are spent accomplishing the most physically demanding tasks (Silva, 2007).

The time budgeting and its relation to inhalation rates and ingestion rates are discussed below.

B. Area and Thickness Considerations

Because the site and the environmental parameters of the deployment site were unknown, it was necessary to make assumptions in regards to area of contamination and thickness of that area. The area of contaminated zone parameter refers to the size of the area that contains the soil samples where radiation is clearly above background (Yu et al., 1993). The thickness of contaminated zone refers to the depth below the surface which contains the samples where radiation is clearly above background (Yu et al., 1993). In this case, the RESRAD program designers define “clearly above background” as the mean background level plus twice the standard deviation of the measurement (Yu et al., 1993).

To calculate a reasonably protective dose rate, it was necessary to find an area and a thickness that is considered very large in comparison to the area occupied by an average Airman. The larger the area is, the less likely it is that the radionuclide concentration in the soil for that entire area is uniform. Therefore, if a small area is sampled but the entire surrounding area is assumed to have the same concentration as the sample, this is a most protective assumption if the sample has a higher concentration than the surrounding area.

This implies that this methodology is optimal for sampling small areas where there is a concern of heightened concentration of radionuclides.

The RESRAD results shown in Figure 1 display dose rates corresponding to different areas assuming all other factors remain constant. The radionuclides used in this calculation were 1 pCi/g of each of the following: uranium-238, uranium-234, thorium-230, radium-226, lead-210, thorium-232, radium-228, thorium-228, uranium-235, protactinium-231, actinium-227, plutonium-241, americium-241, neptunium-237, uranium-233, thorium-229, cobalt-57, cobalt-60, cesium-134, cesium-137, europium-152, europium-154, and iridium-192 (pCi/g is the standard unit of radionuclide concentration in RESRAD). These radionuclides were measured in the USACHPPM gamma-screen or in a decay series with those that were measured. The thickness used to generate Figure 1 was the default value of 2 meters. All other factors were set for the program default values.

As shown on Figure 1, over 80% of the total dose was from external exposure (data from Figure 1 are shown in Appendix A). When considering areas over 1 square kilometer, adding more area no longer increased the dose rate. Therefore, an area of 1 square kilometer (10^6 m^2) was considered infinite for purposes of these exposures.

Using this area assumed the radionuclide concentration was uniform over this area. Therefore, the entire area had the same radionuclide concentration as the sample entered into RESRAD. If the area sampled was of elevated concentration, this assumption would give a more protective dose since the dose

rate would be calculated such that the entire area had that elevated concentration. Conversely, if the sample had a lower concentration than the surrounding areas, this assumption would be less protective.

For high concentrations that are centralized in one spot such as radiological accidents or spills, considerations need to be made that are outside of the scope of this study. It is likely that such elevated areas of activity, if sampled, would exceed the screening levels proposed here and would be followed up with additional analysis.

Figure 1: Variations in Dose Rate due to Contaminated Area Size

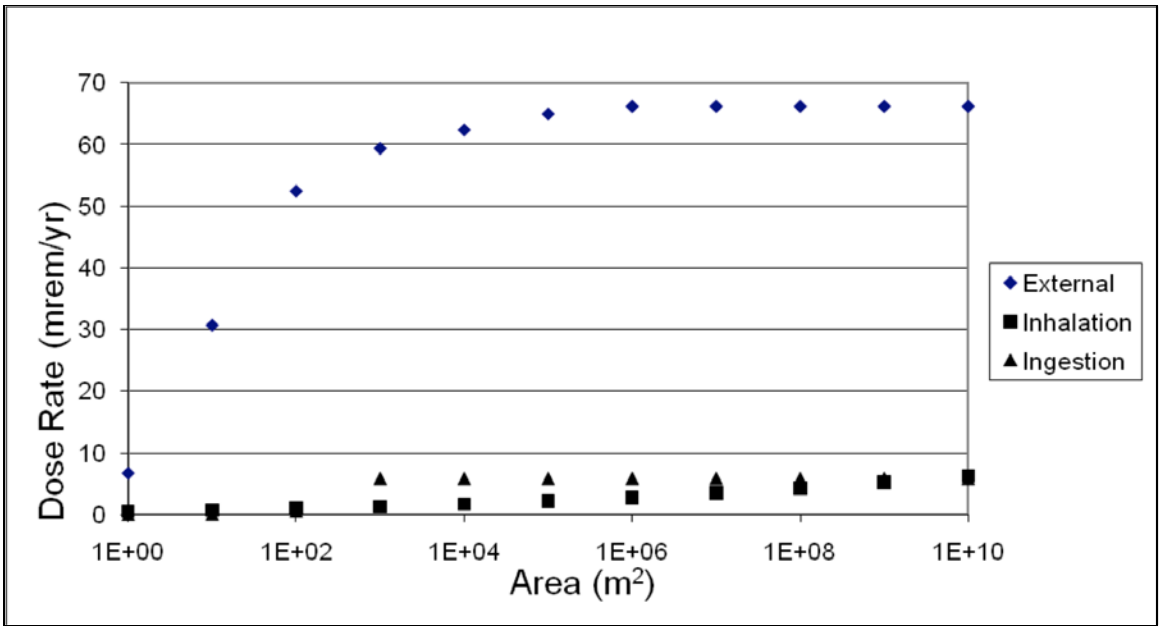
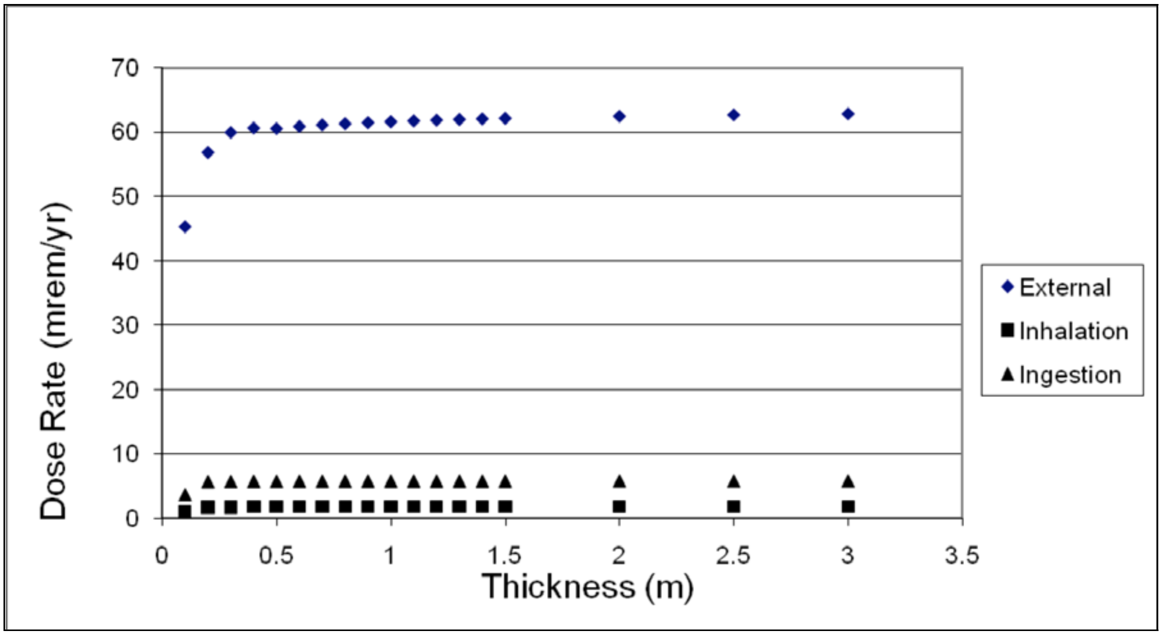


Figure 2 (see Appendix A for data) shows a similar test, calculated this time with varying thickness of contamination and a constant area. For the area, the default value of 10,000 square meters was used. All other factors were the same as they were in the previous data analysis used to generate Figure 1.

Figure 2: Variations in Dose Rate due to Contaminated Soil Thickness



The results show that for thicknesses over one meter, there is a negligible change in the results. The thickness of 2 meters is the RESRAD default value. Typically, only the top 15 cm is sampled. Since changing the thickness from 0.5 m to 2 m causes no significant change in the external dose, a conservative assumption of 1 meter as the thickness depth was used based on the inspection of Figure 2. Again, if there is reason to believe that the soil is significantly non-uniform over this depth, additional considerations such as those described in MARSSIM are required which are outside of the scope of this study.

It was assumed for the purposes of this study that no uncontaminated cover soil existed. Making the assumption of no cover made this measurement more conservative, since there was no uncontaminated soil to shield from the contaminated soil below. Therefore, the default parameter for RESRAD of a 0 meter cover depth was used.

C. Time Budgeting for Military Personnel

The results of the analysis of any given soil sample were assumed to be representative of the environment to which the Airmen were exposed.

The ICRP 89 average for time spent outside is 2 hours per day. However, this estimate is considering average citizens; it was necessary to make a conservative approximation for Airmen who have outdoor jobs as well as exercise outdoors.

First, the Airmen are assumed to receive 8 hours of (indoor) sleep a day. For the remaining 16 hours, 12 hours are spent outside (exercising, working, or traveling) with the remaining 4 hours spent inside. This gives a total of 12 hours spent outside and 12 hours spent inside.

Assuming the Airmen spend 4 hours inside awake; the ICRP 66 consideration of one-third sitting awake and two-thirds light exercise was employed. As for the outdoor time, about 6 of the 12 hours spent outside are assumed to be spent doing the heaviest work such as lifting and moving heavy freight based on data acquired from currently deployed personnel (Silva, 2007).

D. Inhalation Rates

Table 4 shows the time budgets and associated breathing rates for persons engaged in physical activities from the ICRP publications. Although the rate for heavy exercise is given for 2 hours only, this rate was assumed for 6 hours as a “most protective” scenario. Therefore, this considers the upper-bound for the most active Airmen, not the typical Airmen.

Table 4: Time Budgeting and Inhalation Rates

Location	Activity	Rate (m^3/h)	Hours	Volume (m^3)
Outside	Light Exercise	1.50	6	9
Outside	Heavy Exercise	3.00	6	18
Inside	Sleeping	0.45	8	3.6
Inside	Sitting Awake	0.54	1.3	0.702
Inside	Light Exercise	1.50	2.7	4.05
		Total	24	35.352

From these data, a breathing rate of 35.352 m^3/day, which is equal to 12903.48 m^3/y, was assumed for the purposes of this study. Reduction to the significant figures of the data yielded an inhalation rate of 13000 m^3/y.

E. Soil Ingestion

Since the deployed Airmen considered in this study are assumed to spend a large portion of their day outside doing work, the EPA suggested results for soil ingestion are a low estimate (Hawley, 1985). Based on the time budgeting used above, a modified soil ingestion rate could be calculated.

Using the results from Hawley’s study, the modified rate was determined to be an average between the indoor ingestion rate of 110 mg/day (the upper limit of his estimation) and the outdoor ingestion rate of 480 mg/day (Hawley, 1985). The two were weighed since a time budget of 12 hours a day inside and 12 outside was initially assumed.

This resulted in an assumed average soil ingestion rate of 295 mg/day, which is equivalent to 107.675 g/y. Therefore, an ingestion rate of 110 g/y was assumed.

F. RESRAD Input Parameters

The calculations performed using RESRAD made use of the following parameters:

Area of contaminated zone: 1,000,000 square meters (1 km^2)

Thickness of contaminated zone: 1 meter

Cover depth: 0 meters (default parameter)

Inhalation rate: 13000 m^3/year

Indoor time fraction: 0.5 (default parameter)

Outdoor time fraction: 0.5

Soil ingestion: 110 grams/year

Set pathways: external gamma, inhalation, and soil ingestion

G. Radionuclides Reported at USACHPPM

The following radionuclides routinely reported at USACHPPM from soil samples are:

-Actinium-228 (Ac-228) is part of the Thorium Series, so it is an indicator of thorium-232. Actinium-228 decays (with a half-life of 6.15 hours) to thorium-228 and it reaches secular equilibrium with thorium-228. Actinium-228 is detected by its decay energy emission peak at 911 keV and a second peak at either 338 or 969 keV.

-Americium-241 (Am-241) is the product of the beta decay of plutonium-241 in the Neptunium Decay Series, which ultimately decays to bismuth-209. Americium-241 has a half-life of 432.7 years and emits an alpha particle to decay

to neptunium-237, which has a very long half-life (2.14×10^6 y). Americium-241 is detected by its decay energy emission peak at 59 keV.

-Bismuth-214 (Bi-214) is a natural decay product and indicator of radium-226, both of which are in the Uranium Series decay chain. Bismuth-214 has a half-life of 19.9 minutes. It emits a beta particle to become polonium-214 (99.98% of decays), or it can emit an alpha particle to become thallium-210 (0.02% of decays). Bismuth-214 is detected by its decay energy emission peak at 609 keV.

-Cesium-134 (Cs-134) is a common product of nuclear fission, which makes it useful for detecting fission products that might be from spent nuclear fuel. It has a half life of 2.065 years. It emits a beta particle while decaying barium-134. It can also undergo electron capture to become xenon-134, but the chance of this is negligibly small (0.00030%). Cesium-134 is detected by decay energy emission peaks at 604 and 795 keV.

-Cesium-137 (Cs-137) is also usually formed by nuclear fission. Its uses include calibration of radiation detectors and in medical therapy devices to treat cancer. It has a half-life of 30.07 years. It emits a beta particle while decaying to barium-137. Cesium-137 is detected by a decay energy emission 661 keV peak emitted by barium-137m.

-Cobalt-57 (Co-57) is commonly used for calibration sources since it emits only gamma rays. It is produced in particle accelerators. It undergoes electron capture to become iron-57. Co-57 has a half life of 271.8 days. Cobalt-57 is detected by decay energy emission peaks at 122 and 136 keV.

-Cobalt-60 (Co-60) is used in industrial radiography to detect flaws in metal products, to sterilize food by killing the bacteria without harming the product, and it has uses in radiation therapy. It is produced by activation from cobalt-59 in nuclear reactors. It has a half-life of 5.271 years and decays to nickel-60. Its decaying emits one beta particle. Cobalt-60 is detected by decay energy emission peaks at 1173 keV and 1332 keV.

-Europium-152 (Eu-152) is not naturally-occurring radionuclide, i.e., it is created by the fission of uranium or plutonium. When a uranium or plutonium atom fissions, it splits into two atoms, one of which can be europium-152. Several neutrons are also emitted in this process. Europium-152 can also be present in an environment in the fallout from nuclear weapons testing. It has a half life of 13.54 years and can decay by emitting a beta particle to become gadolinium-152 (27.90% of decays) or by electron capture to become samarium-152 (72.10% of decays). The presence of europium-152 is confirmed in a sample based on detection of energy emission peaks at 344 and 122 keV.

-Europium-154 (Eu-154) is another fission product. It emits a beta particle while decaying to gadolinium-154 with a half life of 8.593 years. The presence of europium-154 is confirmed in a sample by detection of an emission peak at 1274 keV and an emission peak at either 123 or 723 keV.

-Iridium-192 (Ir-192) is an isotope that is commonly used in cancer therapy and industrial radiography. It is produced by activation from iridium-191 in nuclear reactors. It has a half-life of 73.83 days and emits a beta particle to

become platinum-192. Iridium-192 is detected by a decay energy emission peak at 316 keV and either a 295, 308, or 468 peak.

-Protactinium-234 metastable (Pa-234m) is the product of thorium-234 in the Uranium Series decay chain. This chain starts with uranium-238, of which Pa-234m is an indicator. Protactinium-234 emits a beta particle to become uranium-234 and has a half-life of 1.17 minutes. The Uranium Series decay chain eventually decays to the stable lead-206. Metastable protactinium-234 is detected by emission peaks at 766 and 1001 keV.

-Thorium-234 (Th-234) is also an indicator of the presence of uranium-238. It is the direct product of uranium-238 in the Uranium Series decay chain. Thorium-234 emits a beta particle and has a half life of 24.10 days. Thorium-234 is detected by emission peaks at 63 and 93 keV.

-Uranium-235 (U-235) is the most common natural fissile isotope. Fissile materials are materials that can undergo spontaneous fission. Fission is the process of an atom splitting into two or more products after absorbing a zero-kinetic energy neutron into the nucleus. Therefore, it is used as fuel in nuclear reactors since its fission can sustain a chain reaction. By weight, about 0.72% of natural uranium is U-235. It has a half-life of 7.04×10^{10} years. It emits an alpha particle to decay to thorium-231. Uranium-235 is in the Actinium Series decay chain, in which it passes through several decays before becoming the stable lead-207. Uranium-235 is detected by emission peaks at 143 and 186 keV as it decays to thorium-231.

H. Secular Equilibrium

Consider a simple decay chain where Isotope 1 decays to Isotope 2, and Isotope 2 decays to Isotope 3. In this case, let the half-life of Isotope 1 be much longer that the half-life of Isotope 2. Therefore, the rate of change of Isotope 2 equals the rate of formation of Isotope 2 (which equals the rate of decay of Isotope 1) minus the rate of decay of Isotope 2.

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \tag{11}$$

N is the number of atoms of an isotope and λ is its decay constant. The number of atoms times the decay constant is equal to the activity (A).

$$A = \lambda N \;\; where \;\; T_{1/2} = \frac{\ln 2}{\lambda} \tag{12}$$

Since Isotope 1 has a much greater half-life than Isotope 2, Isotope 2 has a much larger decay constant (λ) than Isotope 1. Solving Equation 11 for the activity of 2 yields:

$$\lambda_2 N_2 = \lambda_1 N_1 (1 - e^{-\lambda_2 t}) \tag{13}$$

If an amount of time (t) has passed that is much larger than the half life of Isotope 2, the exponent in Equation 13 becomes very small.

$$As \quad t \rightarrow \infty \quad then \quad (1 - e^{-\lambda_2 t}) \rightarrow 1 \tag{14}$$

Therefore, we find:

$$\lambda_2 N_2 = \lambda_1 N_1$$

$$A_1 = A_2 \tag{15}$$

Therefore, activities of the parents and progeny are the same after a sufficient period of time. This condition is referred to as secular equilibrium. The numbers of atoms (which are proportional to the mass) are related to the activity by the decay constant, which is inversely proportional to the half life of the isotope. Therefore, two isotopes that are in secular equilibrium have the same activity (and therefore the same concentration in soil).

Several of the radionuclides listed above are indicators of the activity in their respective decay chains. The four natural decay chains are shown in the next section.

The radionuclides that have half-lives less than 30 days cannot be entered into RESRAD. These are indicators of the concentration of the longer-lived radionuclides once secular equilibrium has been reached, which RESRAD assumes (Yu et al., 2001). For every radionuclide, it was necessary to assume secular equilibrium since every radionuclide is not usually measured.

Note that the minimum half-life of radionuclides that can be entered into RESRAD is variable (1 day, 7 days, 30 days, or 180 days). For the purpose of this study, it is necessary to include radionuclides that will exist in a significant quantity for more than 6 months. For example, if a radionuclide has a half-life of 8 days, it will not be detectable after about 56 days (seven half-lives) unless there was a very large amount to begin with, so it won't be a source of dose for the

entire 6 months. Therefore, radionuclides that have a half-life of less than 30 days are not considered for this analysis.

I. The Decay Series and Their Relation to Soil Analysis

1. Uranium Series

For the Uranium Series, thorium-234 and protactinium-234m are measured as indicators of the series down to thorium-230. It is necessary to wait seven half-lives of protactinium-234m (about 8.2 minutes) after the sample is taken before measuring to ensure that protactinium-234m is in secular equilibrium with thorium-234. The larger of those two concentrations can be entered into RESRAD as the concentrations of uranium-238, uranium-234, and thorium-230. A decay of thorium-234 or protactinium-234m will eventually yield 3 alpha particles and 2 beta particles.

Bismuth-214 was analyzed as an indicator of the rest of the Uranium Series decay chain, which starts with radium-226 and ends with lead-206. Therefore, the concentration of bismuth-214 was entered into RESRAD as the concentration of radium-226, lead-210, and polonium-210. A decay of bismuth-214 will eventually yield 5 alpha particles and 4 beta particles.

Four radionuclides that occur in this chain (protactinium-234, astatine-218, thallium-210, and thallium-206) are not listed below. These radionuclides are neglected due to the small fraction (<1%) of abundance.

The total emissions for a decay of the entire Uranium Series is 8 alpha particles and 6 beta particles.

Table 5: Uranium Series

Radionuclide	Half-life	Probable Emission Type	In RESRAD's Database?	Measured in analysis?
Uranium-238	4,470,000,000 y	alpha	yes	no
Thorium-234	24.1 d	beta	no	yes
Protactinium-234m	1.17 min	beta	no	yes
Uranium-234	246,000 y	alpha	yes	no
Thorium-230	75,400 y	alpha	yes	no
Radium-226	1,599 y	alpha	yes	no
Radon-222	3.8235 d	alpha	no	no
Polonium-218	3.10 min	alpha	no	no
Lead-214	27 min	beta	no	no
Bismuth-214	19.9 min	beta	no	yes
Polonium-214	163.7 μsec	alpha	no	no
Lead-210	22.3 y	beta	yes	no
Bismuth-210	5.01 d	beta	no	no
Polonium-210	138.38 d	alpha	yes	no
Lead-206	Stable	none	no	no

Source: (Cember, 1996)

2. Thorium Series

The only radionuclide in the Thorium Series that was measured for in the analyses is actinium-228. For this series to be in secular equilibrium with its parent (radium-228), it takes seven half lives of actinium-228 (about 43 hours). The rest of the chain was assumed to be in secular equilibrium. Therefore, the concentration of actinium-228 was entered into RESRAD as the concentrations of the long-lived radionuclides thorium-232, radium-228, and thorium-228.

The decay of bismuth-212 can have two results. If bismuth-212 emits an alpha particle to decay to thallium-208, the thallium-208 atom will emit a beta particle to decay to lead-208. If bismuth-212 emits a beta particle to decay to polonium-212, the polonium-212 atom will emit an alpha particle to decay to lead-208. Therefore, the number of alphas and betas will be consistent for either branch. A thorium-232 atom will eventually result in the emission of 6 alpha particles and 4 beta particles.

Table 6: Thorium Series

Radionuclide	Half-life	Probable Emission Type	In RESRAD's Database?	Measured in analysis?
Thorium-232	14,100,000,000 y	alpha	yes	no
Radium-228	5.76 y	beta	yes	no
Actinium-228	6.15 hr	beta	no	yes
Thorium-228	1.912 y	alpha	yes	no
Radium-224	3.66 d	alpha	no	no
Radon-220	55.6 sec	alpha	no	no
Polonium-216	0.145 sec	alpha	no	no
Lead-212	10.64 hr	beta	no	no
Bismuth-212	1.009 hr	alpha (33.7%), beta (66.3%)	no	no
Polonium-212 (66.3%)	0.298 μsec	alpha	no	no
Thallium-208 (33.7%)	3.053 min	beta	no	no
Lead-208	Stable	none	no	no

Source: (Cember, 1996)

3. Actinium Series

The Actinium Series starts with uranium-235, which is about 0.7% of natural uranium (Cember, 1996). Uranium-235 is the most useful isotope for nuclear fission purposes, so it is a possible indicator of past reactor activity in the area sampled. For this reason, uranium-235 is the only radionuclide in this series that is measured, so secular equilibrium is assumed for the entire series. A uranium-235 atom will eventually result in the emission of 7 alpha particles and 4 beta particles.

Three radionuclides (francium-223, astatine-215, and polonium-211) are not listed below that occur in this chain. These radionuclides were neglected due to their small (<2%) abundance.

Table 7: Actinium Series

Radionuclide	Half-life	Probable Emission Type	In RESRAD's Database?	Measured in analysis?
Uranium-235	704,000,000 y	alpha	yes	yes
Thorium-231	1.063 d	beta	no	no
Protactinium-231	32,800 y	alpha	yes	no
Actinium-227	21.772 y	beta	yes	no
Thorium-227	18.68 d	alpha	no	no
Radium-223	11.435 d	alpha	no	no
Radon-219	3.96 sec	alpha	no	no
Polonium-215	1.781 msec	alpha	no	no
Lead-211	36.1 min	beta	no	no
Bismuth-211	2.14 min	alpha	no	no
Thallium-207	4.77 min	beta	no	no
Lead-207	Stable	none	no	no

Source: (Cember, 1996)

4. Neptunium Series

The Neptunium Series is the only series that is no longer naturally occurring. The members of this series should not be found in soil samples other than in trace amounts unless there is man-made radioactive materials or activities in the area sampled.

Americium-241 is the only radionuclide measured in this series due to the time constraints of analyzing for all of the radionuclides in this series. Therefore, it was necessary to assume secular equilibrium for the entire series. The concentration of americium-241 was entered into RESRAD as the concentration for the five long-lived radionuclides in this series: plutonium-241, americium-241, neptunium-237, uranium-233, and thorium-229. Decay of a plutonium-241 atom will eventually result in the emission of 8 alpha particles and 5 beta particles.

Two radionuclides that occur in this chain (uranium-237 and thallium-209) are not listed below due to the fact these radionuclides have only a small chance (<3%) of natural occurance.

Table 8: Neptunium Series

Radionuclide	Half-life	Probable Emission Type	In RESRAD's Database?	Measured in analysis?
Plutonium-241	14.4 y	beta	yes	no
Americium-241	432.7 y	alpha	yes	yes
Neptunium-237	2,140,000 y	alpha	yes	no
Protactinium-233	26.967 d	beta	no	no
Uranium-233	159,200 y	alpha	yes	no
Thorium-229	7,300 y	alpha	yes	no
Radium-225	14.9 d	beta	no	no
Actinium-225	10.0 d	alpha	no	no
Francium-221	4.8 min	alpha	no	no
Astatine-217	0.032 sec	alpha	no	no
Bismuth-213	45.6 min	beta	no	no
Polonium-213	3.8 μs	alpha	no	no
Lead-209	3.25 hr	beta	no	no
Bismuth-209	Stable	none	no	no

Source: (Cember, 1996)

Due to fallout from nuclear weapons testing, this series will be found in the background in small amounts. There are not extensive data on ranges of concentration of americium-241 in soil worldwide. The average worldwide concentration of americium-241 in the top 30 cm of soil is 0.0033 Bq/g (0.0892 pCi/g), so the concentration should be on the order of 0.1 pCi/g or less. If americium-241 is detected in large amounts in soil from a deployment location, precautions and procedures should be performed that are outside the scope of this study (Agency for Toxic Substances and Disease Registry, 2004).

J. Gamma Emission Analysis

To find concentrations that relate to a given dose rate, it was first necessary to determine the relationship between them. Data from RESRAD that shows this is presented in Appendix B.

The dose rates calculated in Table 9 are for 1 pCi/g of each of the radionuclides mentioned above as inputs. This measurement is a reference point

which can be scaled to the dose limit being applied, so they will be referred to as the reference concentrations. Selected RESRAD results for this analysis are shown in Appendix C.

Table 9: RESRAD Outputs for the Reference Concentration

Radionuclide	Radionuclide Concentration (pCi/g)	TEDE Rate (mrem/y)	Series
U-238	1	1.867E-01	Uranium
U-234	1	6.339E-02	Uranium
Th-230	1	1.427E-01	Uranium
Ra-226	1	9.621E+00	Uranium
Pb-210	1	7.017E-01	Uranium
Po-210	1	9.586E-02	Uranium
Th-232	1	1.060E+00	Thorium
Ra-228	1	6.282E+00	Thorium
Th-228	1	7.393E+00	Thorium
U-235	1	7.009E-01	Actinium
Pa-231	1	1.712E+00	Actinium
Ac-227	1	4.856E+00	Actinium
Pu-241	1	9.749E-03	Neptunium
Am-241	1	5.407E-01	Neptunium
Np-237	1	1.552E+00	Neptunium
U-233	1	6.573E-02	Neptunium
Th-229	1	2.328E+00	Neptunium
Co-57	1	2.765E-01	None
Co-60	1	1.290E+01	None
Cs-134	1	6.843E+00	None
Cs-137	1	2.872E+00	None
Eu-152	1	5.797E+00	None
Eu-154	1	6.269E+00	None
Ir-192	1	7.825E-01	None

For the radionuclides in radionuclide series, the dose rate from the measured radionuclide is the sum of all of the dose rates from radionuclides in series with it. For example, the only radionuclide measured in the Thorium Series is actinium-228. Therefore, the dose rate from actinium-228 is the sum of the dose rates of thorium-232, radium-228, and thorium-228, which are the only radionuclides in the Thorium Series with half-lives over 30 days. The dose rate

(D_i) associated with the reference concentration of each of the 13 measured radionuclides is shown in Table 10.

$$D_{Th-234,R} = D_{U-238} + D_{U-234} + D_{Th-230} \tag{16}$$

$$D_{Pa-234m,R} = D_{U-238} + D_{U-234} + D_{Th-230} \tag{17}$$

$$D_{Ac-228,R} = D_{Th-232} + D_{Ra-228} + D_{Th-228} \tag{18}$$

$$D_{Bi-214,R} = D_{Ra-226} + D_{Pb-210} + D_{Po-210} \tag{19}$$

$$D_{U-235,R} = D_{U-235} + D_{Pa-231} + D_{Ac-227} \tag{20}$$

$$D_{Am-241,R} = D_{Pu-241} + D_{Am-241} + D_{Np-237} + D_{U-233} + D_{U-229} \tag{21}$$

D_i = dose rate from 1 pCi/g (mrem/y) of radionuclide i from RESRAD (shown in Table 9)

$D_{i,R}$ = dose rate represented by 1 pCi/g (mrem/y) of radionuclide i, assuming all radionuclides in series are in secular equilibrium (shown in Table 10).

Table 10: Dose Rate for Reference Concentrations of 13 Reported Nuclides As Calculated By RESRAD

Radionuclide	Radionuclide Concentration (pCi/g)	TEDE Rate (mrem/y)
Th-234	1	3.928E-01
Pa-234m	1	3.928E-01
Bi-214	1	1.042E+01
Ac-228	1	1.474E+01
U-235	1	7.269E+00
Am-241	1	4.496E+00
Co-57	1	2.765E-01
Co-60	1	1.290E+01
Cs-134	1	6.843E+00
Cs-137	1	2.872E+00
Eu-152	1	5.797E+00
Eu-154	1	6.269E+00
Ir-192	1	7.825E-01

In Table 10, the dose rate for each of these radionuclides is the sum of the dose rate from each of the radionuclides in their respective series, assuming the series are in secular equilibrium with their progeny. For example, the dose from 1 pCi/g of U-235 is the sum of the doses from 1 pCi/g of each of the long-lived radionuclides in the actinium series, assuming secular equilibrium.

Concentrations were calculated for three dose rate limits. The first is 0.05 rem (or 50 mrem) in a year, which is RES category 0 according to Air Force Instruction 48-148 (US Air Force, 2001). This limit applies only if there is one deployment per year. A deployment is defined as “The relocation of forces and material to desired areas of operations. Deployment encompasses all activities from origin or home station through destination, specifically including within the United States, inter-theater, and intra-theater movement legs, staging, and holding areas.” (US Air Force, 2005) If the deployment lasts more than a year, the results should be scaled appropriately. This limit is the lowest limit to be

considered since if the dose rate was below this level, no intervention is necessary beyond routine monitoring of the area.

The second is the limit for occupationally exposed radiation workers, which is 5 rem in one year stated in 10 CFR 20 (Nuclear Regulatory Commission, 1991). This limit applies to workers who are under United States jurisdiction; radiation workers from other countries do not adhere to this limit.

The third dose rate is the general public limit of 0.1 rem (100 mrem) for NRC-licensed operations, as stated in 10 CFR 20 (Nuclear Regulatory Commission, 1991). This limit applies to non-radiation workers and residents who are under United States jurisdiction; citizens from other countries do not follow this guideline.

Using linear scaling, Table 11 shows the concentration corresponding to the stated dose for each radionuclide.

Table 11: Radionuclide Concentration Limits for Dose Rate Limits (pCi/g) From RESRAD and Linear Scaling

Radionuclide	50 mrem/y limit	5 rem/y limit	0.1 rem/y limit
Th-234	1.273E+02	1.273E+04	2.546E+02
Pa-234m	1.273E+02	1.273E+04	2.546E+02
Bi-214	4.799E+00	4.799E+02	9.598E+00
Ac-228	3.393E+00	3.393E+02	6.787E+00
U-235	6.879E+00	6.879E+02	1.376E+01
Am-241	1.112E+01	1.112E+03	2.224E+01
Co-57	1.808E+02	1.808E+04	3.617E+02
Co-60	3.876E+00	3.876E+02	7.752E+00
Cs-134	7.307E+00	7.307E+02	1.461E+01
Cs-137	1.741E+01	1.741E+03	3.482E+01
Eu-152	8.626E+00	8.626E+02	1.725E+01
Eu-154	7.976E+00	7.976E+02	1.595E+01
Ir-192	6.390E+01	6.390E+03	1.278E+02

Th-234 and Pa-234m are surrogates for U-238. Bi-214 is a surrogate for Ra-226. Ac-228, U-235, and Am-241 are surrogates for the Thorium Series, Actinium Series, and Neptunium Series, respectively. Radionuclides that are surrogates for a series have the same activity as every other long-lived radionuclide in the series. For example, 1 pCi/g of Am-241 represents 1 pCi/g of every radionuclide in the Neptunium Series.

Dividing each concentration measurement by its respective limit gave a percentage of the total dose allowed. Therefore, the condition for remaining below the dose limit was derived by making use of the unity rule.

$$\frac{C_{U\,Series}}{(C_{\lim})_{U\,Series}} + \frac{C_{Bi-214}}{(C_{\lim})_{Bi-214}} + \frac{C_{Ac-228}}{(C_{\lim})_{Ac-228}} + \frac{C_{U-235}}{(C_{\lim})_{U-235}} + \frac{C_{Co-57}}{(C_{\lim})_{Co-57}} \cdots$$

$$+ \frac{C_{Co-60}}{(C_{\lim})_{Co-60}} + \frac{C_{Cs-134}}{(C_{\lim})_{Cs-134}} + \frac{C_{Cs-137}}{(C_{\lim})_{Cs-137}} + \frac{C_{Eu-152}}{(C_{\lim})_{Eu-152}} + \frac{C_{Eu-154}}{(C_{\lim})_{Eu-154}} \cdots$$

$$+ \frac{C_{Ir-192}}{(C_{\lim})_{Ir-192}} + \frac{C_{Am-241}}{(C_{\lim})_{Am-241}} \leq 1 \tag{22}$$

where the following definitions are established:

C_i = measured concentration of radionuclide i (pCi/g)

$(C_{lim})_i$ = concentration limit of radionuclide i from Table 11 (pCi/g)

$C_{U\ series}$ = measured concentration of the Uranium Series, which is assumed to be in secular equilibrium, represented as the concentration of thorium-234 or protactinium-234m, whichever is higher (pCi/g)

$(C_{lim})_{U\ Series}$ = concentration limit of the Uranium Series, represented as the concentration limit of thorium-234 or protactinium-234m from Table 11 (pCi/g)

If not all of these radionuclides are reported, the above function can be modified by setting the fractions of the unavailable radionuclides equal to zero. However, this function becomes less useful since it was assumed that radionuclides not in Equation 22 are not present in the area of interest. However, all information regarding presence of individual radionuclides may become useful in analyzing gross alpha/beta limits, as will be discussed later in this study.

If the concentration of each of these individual radionuclides is available, Equation 22 can be used to show the TEDE is below the dose limit. Use of Equation 22 assumes that these radionuclides (the 13 listed above as well as any in the four series) were the only ones present in the soil. Also, since no information on background levels is typically available, Equation 22 takes into account the background dose as part of the dose rate limit.

However, most of the radionuclides accounted for in Equation 22 are not naturally occurring, so they will not appear in soil in any ratio unless human activity is present. Therefore, there is no gross alpha/beta level relating to the data above. In measuring the gross beta, for example, there is no way of knowing an individual radionuclide’s contribution to the overall gross beta counting rate. To obtain a gross alpha/beta screening level to relate to these dose rates, it is necessary to study the dose from radionuclides that appear naturally in soil to calculate the alpha/beta concentrations naturally emitted by

soil. This is necessary to understand since the dose rate limits regulate dose above background.

K. Natural Radionuclides in Soil

Of the four decay series, three (uranium, thorium, and actinium) appear naturally in soil. Also, a number of non-series primordial (existing since Earth's beginning) radionuclides appear naturally in soil. However, only two of these- potassium-40 (K-40) and rubidium-87 (Rb-87) are of interest in considering dose estimates (Eisenbud, 1997).

Table 12 shows the worldwide average concentrations of the four most prominent radionuclides in soil.

Table 12: Median Concentrations in Soil of Natural Radionuclides

Radionuclide	Concentration (pCi/g)	Range (pCi/g)
U-238	0.946	16 - 110
Th-232	0.811	11 - 64
K-40	10.81	140 - 850
Rb-87	1.4	-

Sources: (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000), (National Council on Radiation Protection & Measurements, 1987)

These values are medians of background concentrations (not the population weighed means) from 41 countries sampled by the United Nations for uranium-238, thorium-232, and potassium-40. Some of the measurements have large variations in activity and some of their activities approach zero for each radionuclide, so no assumptions can be made about a minimum background (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000). The ranges presented in Table 12 are the ranges of means from individual countries.

Natural uranium is composed of approximately 99.3% uranium-238, 0.7% uranium-235, and 0.005% uranium-234 (Cember, 1996). Uranium-234 will assumed to be in secular equilibrium with uranium-238 for purposes of this study. Uranium-234 appears naturally in much smaller masses because it has a half life that is much shorter than the half life of uranium-238. Uranium-235, however, is not part of the uranium-238 series.

The specific activity of a radionuclide is the activity per unit mass of that isotope. Uranium-235 and uranium-238 have specific activities of 2.16×10^{-6} Ci/g and 3.37×10^{-7} Ci/g, respectively. Assuming 1 gram of soil, a concentration of uranium-235 in the soil can be derived from the concentration of uranium-238 (0.946 pCi/g). This calculation was performed as follows:

1 g of soil × (0.946×10^{-12} Ci/g) = 9.46×10^{-13} Ci in 1 g soil

9.46×10^{-13} Ci ÷ (3.37×10^{-7} Ci/g) = 2.81×10^{-6} g U-238 in 1 g soil

2.81×10^{-6} g × (0.007 U-235 / 0.993 U-238) = 1.98×10^{-8} g U-235 in 1 g soil

1.98E-8 g × (2.16×10^{-6} Ci/g) = 4.28×10^{-14} Ci of U-235 in 1 g soil

Therefore, the concentration of uranium-235 in soil was calculated to be 0.0428 pCi/g. This activity was used for the activity of the actinium series in secular equilibrium.

Using the parameters for a deployment scenario described earlier in this study, the dose rate from the natural radionuclides were calculated by RESRAD and are shown in Table 13. The RESRAD results for this analysis are shown in Appendix C.

Table 13: RESRAD Results for Natural Radionuclides

Radionuclide	Input Concentration (pCi/g)	Dose Rate Output (mrem/y)
U-238	0.946	1.766E-01
U-234	0.946	5.997E-02
Th-230	0.946	1.350E-01
Ra-226	0.946	9.102E+00
Pb-210	0.946	6.638E-01
Po-210	0.946	9.068E-02
Th-232	0.811	8.594E-01
Ra-228	0.811	5.095E+00
Th-228	0.811	5.996E+00
U-235	0.0428	3.000E-02
Pa-231	0.0428	7.327E-02
Ac-227	0.0428	2.078E-01
K-40	10.81	9.299E+00
Rb-87	1.4	9.252E-04
Total		3.179E+01

The dose rates in Table 13 include dose rates from short-lived progeny of the listed radionuclides. Therefore, these radionuclides produce a total dose of about 31.8 mrem/y.

L. Natural Gross Alpha/Beta Limits

To determine the concentrations of these natural radionuclides which result in a total dose (0.05 rem/y, 5 rem/y, and 0.1 rem/y), a linear scaling of the dose rate versus concentration was performed. Linear scaling is defined as multiplying two directly proportional variables by the same constant. For linear scaling of dose rate and concentration to be possible, these two variables are required to be directly proportional. The direct proportionality of dose rate and concentration are shown in Appendix B. The results of linear scaling are shown in Table 14.

Table 14: Radionuclide Concentration Limits (pCi/g) for Specific Dose Rates From RESRAD And Linear Scaling

Radionuclide	0.05 rem/y limit	5 rem/y limit	0.1 rem/y limit
U-238	1.49	149	2.98
U-234	1.49	149	2.98
Th-230	1.49	149	2.98
Ra-226	1.49	149	2.98
Pb-210	1.49	149	2.98
Po-210	1.49	149	2.98
Th-232	1.28	128	2.55
Ra-228	1.28	128	2.55
Th-228	1.28	128	2.55
U-235	0.0673	6.73	0.135
Pa-231	0.0673	6.73	0.135
Ac-227	0.0673	6.73	0.135
K-40	17.00	1700	34.00
Rb-87	2.2	220	4.4

Rubidium-87 is a pure beta emitter. Potassium-40 decays by beta emission in about 90% of its decays (Shleien, Slaback jr., & Birky, 1998). As described previously, the Uranium Series emits 8 alphas and 6 betas (Table 5), the Thorium Series emits 6 alphas and 4 betas (Table 6), and the actinium series emits 7 alphas and 4 betas (Table 7). Secular equilibrium of these series was once again assumed. The gross alpha and beta emission rate is simply the sum of the alpha/beta rate of the individual radionuclides:

$$C_\alpha = [8 \times C_{U-238}] + [6 \times C_{Th-232}] + [7 \times C_{U-235}] \tag{23}$$

$$C_\beta = [6 \times C_{U-238}] + [4 \times C_{Th-232}] + [4 \times C_{U-235}] + [0.893 \times C_{K-40}] + [1 \times C_{Rb-87}] \tag{24}$$

C_i = concentration limit of radionuclide i from Table 14 (pCi/g)

C_α = gross alpha concentration limit (pCi/g) shown in Table 15

C_β = gross beta concentration limit (pCi/g) shown in Table 15

Using the number of alpha particles and beta particles emitted by each of these decays, Table 15 shows the gross alpha/beta limits for these dose rate limits.

Table 15: Gross Alpha/Beta Limits For Natural Radionuclides (pCi/g) From RESRAD And Linear Scaling

Type	0.05 rem/y limit	5 rem/y limit	0.1 rem/y limit
Alpha	20.1	2000	40.1
Beta	31.7	3170	63.4

These gross alpha/beta limits apply only to natural radionuclides in secular equilibrium. This does not account for any of the radionuclides from reactors, industrial, or medical use: i.e., it assumes that all the gross alpha/beta activity and dose in the environment are due to naturally occurring radionuclides, which might not be true.

To get a more protective limit, the alpha and beta limits above the natural background levels were calculated as though they originated from the radionuclides with the highest dose rate per alpha/beta concentration. Therefore, it was necessary to find out which radionuclide has the most total dose associated with 1 pCi_{β}/g. Similarly, it was necessary to find out which radionuclide has the most total dose associated with 1 pCi_{α}/g.

N. Radionuclides with Highest Dose Rates

Long-lived radionuclides from reactor waste, research, or medical purposes may be present in the area of concern that contribute dose above background. However, only radionuclides with half-lives over 30 days will be considered because very short-lived radionuclides won’t likely give consistent

dose for the entire deployment time considered. Furthermore, they likely won't be detected because of delays in sampling, shipping, and analysis. Due to these delays, the very short-lived radionuclides will not be present in detectable amounts by time the sample is analyzed since they will mostly have decayed.

Isotopes used for medical purposes typically have short half-lives. The most common isotopes in nuclear medicine have half-lives of less than 30 days with the exception of strontium-89, iodine-125, and cobalt-57 (Bushberg, Seibert, Leidholdt Jr., & Boone, 2002). However, products from reactors and accelerators include long lived isotopes such as cesium-137 and europium-154.

Total dose rates per 1 pCi/g in soil for several isotopes from these sources are shown in Appendix D. The dose rate associated with each isotope was divided by the number of alpha particles emitted per decay to yield a dose rate due to an isotopic concentration of 1 pCi_{α}/g. Similarly, the dose rate associated with each isotope was divided by the number of beta particles emitted per decay to yield a dose rate due to an isotopic concentration of 1 pCi_{β}/g. These numbers were used for comparison purposes; it is necessary to know the maximum dose that could be indicated by a single alpha (or beta) particle emitted from a soil sample.

The beta emitter with the largest total dose per 1 pCi_{β}/g is europium-152. The alpha emitter with largest total dose per 1 pCi_{α}/g is radium-226. See Appendix D for a comparison of the long-lived isotopes considered.

Information on background concentrations are typically not included with samples, so no assumptions could be made regarding the background

alpha/beta count in individual soil samples. Generally, exposure to natural background radiation is not regulated; therefore, the screening guidelines developed here were for gross alpha/beta levels above background. If background samples are included with the sample from the area of interest, special considerations could be made that are beyond this study.

O. Gross Alpha/Beta Limits

Using europium-152 as the highest dose per 1 pCi_β/g radionuclide and radium-226 as the highest dose per 1 pCi_α/g radionuclide, new gross alpha/beta limits can be derived. According to Table 13, the average natural radionuclides equate to a total dose of 31.8 mrem/y. Making use of the same equations used to calculate the gross alpha/beta limits for natural radionuclides, this 31.8 mrem/y corresponds to 12.7 pCi_α/g and 20.1 pCi_β/g.

The dose from the activity above average background can come from pure alpha emitters (such as Pu-238, Pu-239, or Pu-240), pure beta emitters (such as Eu-152 or Co-60) or radionuclides that emit both (such as U-238 or Ra-226). Therefore, gross alpha/beta limits could not be expressed as unique, discrete values for alpha and beta; a mathematical relationship relating alpha activity and beta activity needed to be derived.

Table 16 displays theoretical screening guidelines for three dose limits if an entire dose above background came from either pure alpha emitters or pure beta emitters. If there is a combination of both in the soil, these limits would not apply. Since this figure only shows the worst-case alphas and betas, the beta

emissions of radium-226 were not accounted for here; a case involving radium-226 will be discussed later.

Table 16: Gross Alpha/Beta Limits for Worst-Case Scenarios

Total Dose Limit	Source	Total Dose (rem/y)	Alpha Emissions (pCi/g)	Beta Emissions (pCi/g)
0.05 rem/y	Natural	0.03179	12.7	20.1
	Europium-152 betas	0.05	-	2.4
	Radium-226 alphas	0.05	20.8	-
	Total	0.13179	33.5	22.5
5 rem/y	Natural	0.03179	12.7	20.1
	Europium-152 betas	5	-	241
	Radium-226 alphas	5	2079	-
	Total	10.03179	2092	261
0.1 rem/y	Natural	0.03179	12.7	20.1
	Europium-152 betas	0.1	-	4.8
	Radium-226 alphas	0.1	41.6	-
	Total	0.23179	54.3	25.0

To be below a dose rate limit, the residual dose over background (D_{res}) must be equal to or less than the specified dose limit (D_{lim}).

$$D_{res} \leq D_{\lim} \tag{25}$$

The residual dose can be divided by the dose indicated by alpha emitter concentrations and the dose indicated by beta emitter concentrations.

$$D_{\alpha,res} + D_{\beta,res} \leq D_{\lim} \tag{26}$$

$$\frac{D_{\alpha,res}}{D_{\lim}} + \frac{D_{\beta,res}}{D_{\lim}} \leq 1 \tag{27}$$

Equation 27 shows that these two fractions must equal less than one. Since dose rate is directly proportional to the concentration of activity in the soil

for any specific radionuclide, these two fractions could be expressed in terms of concentration.

$$\frac{C_{\alpha,res}}{C_{\lim}} + \frac{C_{\beta,res}}{C_{\lim}} \leq 1 \tag{28}$$

The concentration that corresponds to the dose rate limit could be expressed as either alpha or beta emission rate per unit mass, both of which are shown on Table 16. The residual concentration of alphas is equal to the gross alpha concentration (C_{α}) minus the assumed natural background alpha concentration ($C_{\alpha,bck}$). Likewise, the residual concentration of betas is equal to the gross beta concentration (C_{β}) minus the assumed background beta concentration ($C_{\beta,bck}$). Refinements to these values can be made if actual background alpha/beta concentrations for these samples are known.

$$\frac{C_{\alpha} - C_{\alpha,bck}}{C_{\alpha,\lim}} + \frac{C_{\beta} - C_{\beta,bck}}{C_{\beta,\lim}} \leq 1 \tag{29}$$

Equation 29 accounted for all three scenarios for dose above background: pure alpha, pure beta, or a combination of both. If the entire dose above background came from radium-226 (assuming a dose rate limit of 0.05 rem/y), calculations using data from Appendix D shows:

$$\frac{1\ pCi/g}{9.621\ mrem/yr} \Rightarrow \frac{20.8\ pCi_{\alpha}/g}{50\ mrem/yr} \Rightarrow \frac{10.4\ pCi_{\beta}/g}{50\ mrem/yr}$$

Adding these alpha and beta concentrations to the average natural background alpha and beta emission (12.7 pCi_α/g and 20.1 pCi_β/g), the resulting gross alpha/beta measurement would be 33.5 pCi_α/g and 30.5 pCi_β/g.

$$\frac{33.5-12.7}{20.8}+\frac{30.5-20.1}{2.4}=5.3$$

For the 0.05 rem/y limit, this would not meet the condition above since the result would be 5.3, so the inequality is not satisfied. Equation 29 eliminates the possibility of a dose indicated by alpha particles and a separate dose indicated by beta particles collectively indicating a dose rate above the limit.

IV. Results

The gross alpha/beta unity condition, in combination with the background alpha/beta activities and the limits from Table 17, provide a conservative, protective limit for gross alpha and beta concentrations in soil samples:

$$\frac{C_{\alpha} - C_{\alpha,bck}}{C_{\alpha,\lim}} + \frac{C_{\beta} - C_{\beta,bck}}{C_{\beta,\lim}} \leq 1 \tag{30}$$

C_{α} = gross alpha count in soil (pCi/g)

C_{β} = gross beta count in soil (pCi/g)

$C_{\alpha,lim}$ = limit for alpha activity above background assuming no other contribution to dose (pCi/g) (shown in Table 17)

$C_{\beta,lim}$ = limit for beta activity above background assuming no other contribution to dose (pCi/g) (shown in Table 17)

$C_{\alpha,bck}$ = alpha activity from background (pCi/g) = 12.7 pCi/g (worldwide average background)

$C_{\beta,bck}$ = beta activity from background (pCi/g) = 20.1 pCi/g (worldwide average background)

Table 17: $C_{\alpha,lim}$ and $C_{\beta,lim}$ for Dose Rate Limits From RESRAD and Linear Scaling

Dose Rate Limit (rem/y)	$C_{\alpha,lim}$ (pCi/g)	$C_{\beta.lim}$ (pCi/g)
0.05	20.8	2.4
5	2079	241
0.1	41.6	4.8

If the analysis of a soil sample satisfies the above inequality, the sampled location is in compliance with this proposed guideline and no further radiological

analyses of the sampler are needed. If not, the dose rate to Airmen occupying the sampled area could be above the dose rate of concern and additional analyses and/or controls are required to guarantee compliance with a dose rate limit.

If the measured alpha or beta activity in the sample is below the natural background, that fraction in Equation 30 should be equal to zero. This caveat is necessary to avoid subtracting a dose, which is not physically possible. Therefore, if the alpha activity of the sample is less than 12.7 pCi_{α}/g (assuming the worldwide average background), the equation reduces to:

$$\frac{C_{\beta} - C_{\beta,bck}}{C_{\beta,\mathrm{lim}}} \leq 1 \qquad (31)$$

However, if the beta activity of the sample is less than 20.1 pCi_{β}/g (assuming the worldwide average background), the equation instead reduces to:

$$\frac{C_{\alpha} - C_{\alpha,bck}}{C_{\alpha,\mathrm{lim}}} \leq 1 \qquad (32)$$

Therefore, 12.7 pCi_{α}/g and 20.1 pCi_{β}/g can be used as conservative limits for gross alpha/beta activity, since they represent the worldwide average background. If the measured gross alpha/beta activity is below these numbers, the dose is below the worldwide average background, so they are in compliance with the dose rate limits and represent a minimization of negative health effects.

V. Discussion

A. Pathway and Scenario Assumptions

Several assumptions were made in the derivation of Equation 30:

- The deployed personnel spend all of their time in the area sampled. If they spend a significant amount of their time off post, other sources of radiation will need to be accounted for. In RESRAD calculations, the dose received by an individual during time off the area samples is assumed to equal zero, so the assumption of no time off post was a conservative assumption.
- The inhalation and ingestion rate of a typical human is variable. The rates used in this study are approximations based on Airmen who perform the most active outdoor physical labor. The uncertainty of these rates will be discussed in the next section.
- The radionuclides in each of the series are in secular equilibrium with their progeny. If this is not the case, there is not an equal activity of every radionuclide in a series, so each of the long-lived radionuclides in each series would need to be measured to calculate the total dose rate. Also, radionuclides with a half-life of less than 30 days are assumed by RESRAD to be in secular equilibrium with their parents. The time delay between sampling and measurement would make it difficult to measure the presence of short-lived radionuclides.
- The samples are representative of the area to which deployed Airmen might be exposed. Refer to MARSSIM (Department Of Defense,

Department Of Energy, Environmental Protection Agency, & Nuclear Regulatory Commission, 2000) for statistical considerations and sampling methodology.

- There are no samples for background alpha/beta emissions from soil in the area being sampled, so worldwide average background concentrations of potassium-40, rubidium-87, natural uranium, and natural thorium are assumed to derive background alpha/beta levels. Background samples would be necessary in a more advanced survey. Average background data for many countries is available in the UNSCEAR 2000 report (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000).
- The resuspended soil in the air has the same radionuclide concentration as the soil on the surface of the ground. This assumption is made by RESRAD's computations.

B. Interpreting Laboratory Results

For each individual soil sample, the lab will usually provide three pieces of information for each of the 13 radionuclides as well as gross alpha and gross beta. These three numbers are the activity (per gram of soil), the uncertainty of the measurement, and the minimum detectable concentration. All of these numbers are given in units of pCi/g.

The minimum detectable concentration (MDC) is the smallest concentration of activity in a sample that can be detected with a 5% Type I error and a 5% Type II error (Knoll, 2000). A Type I error in this case is defined to be the chance of detecting this isotope in the soil when there is none actually

present. A Type II error in this case is defined to be the chance of not detecting this isotope when it actually is present. The MDC is used for statistical considerations. However, for the purpose of this study, only concentration data is used for analysis; the MDC and uncertainty are now considered here.

Radioanalytical results will often include negative activity concentrations for individual radionuclides. Before reading a sample, a detector records the ambient radiation and subtracts those results from the sample readings. Due to the uncertainty in both of these measurements, it is possible that the ambient radiation reading is larger than the sample reading, thus resulting in a negative activity result. For the purpose of this study, negative results were considered zero for three reasons. First, it is physically impossible to have negative activity. Second, the results for an individual sample will not be averaged will results from other samples (theoretically, if an infinite number of readings of the same sample were averaged where there is no activity present, the average activity would be zero). Third, considering these samples zero will be conservatively censoring the data, since using a negative number in an equation would result in a negative dose.

The results for the various samples were interpreted individually, not averaged. This was done to separate the areas that can be occupied by Airmen from those that cannot be occupied.

C. Using Gamma Spectroscopy Results

The gamma results are not sufficient for the identification and analysis of all radionuclides in the soil sample. They do not have a background that can be

easily assumed as the gross alpha/beta analysis does, and typically only 13 isotopes are identified and reported. However, these results can be useful in identifying radionuclides that might indicate potential problems or if the sample fails the gross alpha/beta condition. Also, the gamma spectroscopy results can be useful to exclude radionuclides from analyses, such as europium-152.

The beta activity associated with europium-152 in very conservative, since it only takes 2.4 pCi_{β}/g of Eu-152 to result in a TEDE of 50 mrem/y. However, if the gamma spectroscopy results indicate that there is an insignificant amount of Eu-152 (below MDC) in the sample, the beta emitter with the next highest doe rate, cobalt-60, can be used. Below is an adjusted $C_{\beta,lim}$ based on cobalt-60.

Table 18: $C_{\beta,lim}$ Based on Cobalt-60

Dose Rate Limit (rem/y)	$C_{\beta.lim}$ (pCi_{β}/g)
0.05	3.9
5	388
0.1	7.8

These values for $C_{\beta,lim}$ are slightly higher than those associated with europium-152, which are shown in Table 17. If europium-152 and cobalt-60 are not significant in the sample (less than MDC), sodium-22 can be considered the upper limit for the dose rate per beta.

Table 19: $C_{\beta,lim}$ Based on Sodium-22

Dose Rate Limit (rem/y)	$C_{\beta.lim}$ (pCi_{β}/g)
0.05	4.5
5	447
0.1	8.9

Sodium-22 is not a radionuclide reported in the gamma spectroscopy analysis, so it cannot be determined whether or not it is there. Therefore, $C_{\beta,lim}$ cannot be further increased without additional analysis.

The factor representing alpha particle limits ($C_{\alpha,lim}$) cannot be easily adjusted since the alpha emitting radionuclides with the highest dose, such as radium-226, are in natural series with other radionuclides.

D. Missed Dose from Unusual Background Scenarios

If the actual background of an area sampled is much smaller than the worldwide average background and no information regarding the background dose is available, there will be a missed dose. A missed dose occurs when dose above background is mistaken for background dose due to the use of worldwide average background dose. This could result in a sample passing the gross alpha/beta unity condition (Equation 30) even though there is actually a dose present which exceeds the dose limit.

For example, consider the extreme case where background dose is zero. Consider a sample with a gross alpha reading below MDC (equal to zero for practical purposes) and a gross beta reading of 10 pCi_{β}/g. If the worldwide average background was assumed due to the abscence of background samples, Equation 30 would give the result of zero regardless of the dose limit, since the gross alpha and gross beta readings are below the assumed background of 12.7 pCi_{α}/g and 20.1 pCi_{β}/g. Therefore, this sample would pass the gross alpha/beta unity condition (Equation 30).

However, if that entire 10 pCi_{β}/g comes from cobalt-60, this concentration indicates 129 mrem/y (using data from appendix D). Therefore, this dose is missed dose. The sample satisfies Equation 30, but there is actually 129 mrem/y over background, which would be significant since it exceeds the 50 mrem/y standard from the AFI48-148. Background data are necessary to use this condition in all areas since background dose is generally not regulated.

E. Uncertainty

The only numbers in Equation 30 that make use of RESRAD are $C_{\alpha,lim}$ and $C_{\beta,lim}$. Therefore, it was necessary to examine the uncertainty that came from assigning a dose rate to 1 pCi/g of europium-152 or radium-226, since this dose rate was scaled to derive $C_{\alpha,lim}$ and $C_{\beta,lim}$.

The RESRAD program has the capability for probabilistic dose analysis to calculate an uncertainty for the resulting dose rate. Probabilistic dose analysis was performed by the dose rate calculation being performed several times (default is 3 sets of 100 observations) with values for some of the variables randomly selected from a distribution. The RESRAD user can choose which variables should be represented by a distribution of values and not just a single value. For some of the variables, RESRAD code chooses the distribution of values (although the user can modify it); for some of the other variables, the user has to select the distribution of values.

For this uncertainty analysis, six variables were chosen to be represented by a distribution:

1. Fraction of time spent indoors on-site - represented by a triangular distribution ranging from 0 to 1 with a mode of 0.5. This accounts for the extreme possibility of Airmen spending all their time indoors or none of their time indoors.
2. Fraction of time spent outdoors on-site – represented by a triangular distribution ranging from 0 to 1 with a mode of 0.5. This accounts for the extreme possibility of Airmen spending all their time outdoors or none of their time outdoors.
3. Inhalation rate – represented by a triangular distribution ranging from 0.45 m^3/h (3942 m^3/y) to 3.00 m^3/hr (26280 m^3/y) with a mode of 13000 m^3/y. The minimum and maximum rates represent respectively the sleeping rate and the heavy exercise rate from ICRP 89 (International Commission on Radiation Protection, 2003). The mode is the average breathing rate determined earlier in this study.
4. Soil ingestion rate – represented by a triangular distribution ranging from 110 mg/day (40.15 g/y) to 480 mg/day (175.2 g/y) with a mode of 110 g/y. The minimum rate and the maximum rate represent the indoor and outdoor rate determined by the EPA (Environmental Protection Agency, 1997). The mode is the average soil ingestion rate determined earlier in this study.
5. Shielding factor for external gamma radiation – this factor is the ratio of the external gamma radiation indoors on-site to the external gamma radiation outdoors on-site (Yu et al., 1993). A bounded lognormal

distribution is the default distribution used to represent this parameter. This distribution has a range of 0.44 to 1, a mean of the underlying normal of -1.3 and a standard deviation of the underlying normal of 0.59. The default value for the shielding factor for external gamma radiation in RESRAD is 0.7.

6. Mass loading for inhalation – this parameter is the concentration of soil particles in the air (Yu et al., 1993). This factor is affected by soil density and resuspension rates, and changing this parameter affects the inhalation dose rate. A continuous linear distribution using eight different values is the default distribution used to represent this parameter: 8 μg/m^3, 16 μg/m^3, 30 μg/m^3, 40 μg/m^3, 60 μg/m^3, 76 μg/m^3, and 100 μg/m^3. The default value of mass loading for inhalation is 0.0001 g/m^3 (100 μg/m^3).

When probabilistic dose analysis was performed with these six parameters, the results were:

Table 20: Uncertainties for Dose Rate from 1 pCi/g of Eu-152 and Ra-226 From RESRAD

Radionuclide	Result* (mrem/y)	Mean (mrem/y)	Standard Deviation (mrem/y)	95% Confidence Interval (mrem/y)
Eu-152	5.797	4.48	1.60	(1.34, 7.62)
Ra-226	9.621	7.46	2.65	(2.27, 12.7)

*The “results” column indicates the RESRAD computations presented in the Results section of this study. This data was calculated without using probabilistic dose analysis.

As shown in Table 20, the result given by RESRAD is larger than the mean of the probabilistic dose analysis for either radionuclide. This occurs because the default values for mass loading for inhalation and shielding factor for

external gamma radiation are conservative: i.e., they are higher than most of the values that can be chosen from their distributions.

The upper and lower dose rates from the 95% confidence intervals would result in a range of values for $C_{\alpha.lim}$ and $C_{\beta.lim}$, which are shown in Table 21.

Table 21: $C_{a.lim}$ and $C_{b.lim}$, Resulting from 95% Confidence Intervals of Dose Rate

Radionuclide	Dose Rate from 1pCi/g (mrem/y)	Alpha Emissions per Decay	Beta Emissions per Decay	Dose Rate Indicated By 1 pCi_{α}/g (mrem/y)	Dose Rate Indicated By 1 pCi_{β}/g (mrem/y)
Eu-152	1.34	0	0.279	0	4.80
Eu-152	7.62	0	0.279	0	27.3
Ra-226	2.27	4	2	0.568	1.14
Ra-226	12.7	4	2	3.18	6.35

If one of these dose rates were scaled to equal a particular dose rate limit, the result would be a range of $C_{\alpha,lim}$ and $C_{\beta,lim}$ values that correspond to the 95% confidence intervals. These values are shown in Table 22.

Table 22: $C_{a,lim}$ and $C_{b,lim}$ values that correspond to the 95% confidence intervals

Dose Rate Limit (rem/y)	Limit	$C_{\alpha,lim}$ (pCI/g)	$C_{\beta,lim}$ (pCi/g)
0.05	Lower	15.7	1.8
	Upper	88.1	10.4
5	Lower	1575	183
	Upper	8811	1041
0.1	Lower	31.5	3.7
	Upper	176.2	20.8

The single results calculated in the “Results” section are much closer to the lower limits of $C_{\alpha,lim}$ and $C_{\beta,lim}$ that the upper limit. This occurs because the default values for external gamma shielding factor and mass loading for inhalation are conservative; they are higher that the most of the values that are

going to be chosen from their respective distributions during a probabilistic dose analysis.

The ranges above are calculated from 95% confidence intervals from a distribution of values for the six variables listed. Although these consider extreme cases for these variables, such as a person spending 24 hours a day outside for the entire deployment, there are numerous other variables in RESRAD for which a single value is assumed.

VI. Conclusion and Recommendations

Equation 30 and Table 17 are useful for verifying that a soil sample indicates a dose to Airmen that is below a dose rate limit in the area from which the sample came. This study is useful for making sure that the area surrounding an isolated contamination can be occupied by Airmen. This study is useful because it can make this assessment using only gross alpha/beta data and no knowledge of concentrations of individual radionuclides. However, the methods of this study are not to be used to replace a base camp assessment. In the presence of unknown man-made radioactivity, further considerations will be necessary that are not addressed in this study.

For future considerations, the results of this study could be modified to be more useful to the military if there is information about background concentration of radionuclides from worldwide deployment locations and potential deployment locales. The national and international regulatory agencies such as the Nuclear Regulatory Commission in the United States set limits for dose above background. Background dose isn't regulated; therefore, an estimate of the residual dose above background was made based on a worldwide average dose from the UNSCEAR 2000 report. More information on background doses for the country or region the Airmen are being deployed to can be used to modify the results of this study.

For example, UNSCEAR 2000 (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000) data shows that the average soil in the United States of America contains 370 Bq/kg (10 pCi/g) potassium-40, 40 Bq/kg

(1.1 pCi/g) of the Uranium Series, and 35 Bq/kg (0.95 pCi/g) of the Thorium Series (also assuming the same 1.4 pCi/g of rubidium-87). Using the same calculation methods from Section L, this would be equal to about 14.8 pCi/g alpha activity and 20.9 pCi/g beta activity. Using this data, the resulting equation could be modified from Equation 30 to:

$$\frac{C_{\alpha}-14.8}{C_{\alpha,\lim}}+\frac{C_{\beta}-20.9}{C_{\beta,\lim}}\leq 1 \tag{33}$$

This equation could be easily modified for any country or region if reliable data for natural radionclides was available. However, such information is limited.

Some of the parameters used in this study are based off very limited data. For example, there have not been many studies regarding soil ingestion rate. This is a consideration for future studies, particularly the variation of soil ingestion rates in different parts of the world. For example, in desert areas, there would be higher soil ingestion rates expected. There are no studies on the soil ingestion rate in desert areas in comparison to the worldwide average soil ingestion rate.

Also, the time budgeting data for Airmen used in this study is based on conversations with individuals; it is not based on studies. A consideration for future studies would be recording time Airmen spend inside and outside as well as time spent doing their most strenuous and active work while on deployment.

The largest influencing factor in external radiation is the external gamma shielding factor, which is highly variable and understudied. Studying this factor would involve obtaining an understanding of the building materials used at

deployment sites. For this study, it would be necessary to have dosimetry data on the amount of external exposure from contaminated soil to a person indoors to compare to the external exposure from the same soil to a person outdoors. This would improve the approximation of how much shielding Airmen receive from being indoors, which would be a large influence on the external dose calculations.

Data verifying this study would involve dosimetry data on deployed Airmen as well as soil samples from the areas which they occupied. This data would be useful for testing the validity of the method presented here.

The methodology and results presented here, in conjunction with the data from the future considerations discussed above, can provide useful information on the safety of a potential deployment site.

Appendix A: RESRAD Data for Variations in Thickness and Area

The following tests were performed to show the dose (in units mrem per year) as a function of contaminated area and the total dose as a function of the depth of the soil contamination (denoted as thickness). The RESRAD input parameters (these estimated are not the same as used in the “Methodology” section) are as follows:

Cover depth: 0 meters (default parameter)

Inhalation rate: 11000 m^3/year

Indoor time fraction: 0.5 (default parameter)

Outdoor time fraction: 0.5

Soil ingestion: 110 grams/year

Set pathways: external gamma, inhalation, and soil ingestion

The default parameter for thickness (2 meters) was used in the area tests. The default area (10,000 meters squared) was used in the thickness tests.

The concentrations used are 1 pCi/g each of uranium-238, uranium-234, thorium-230, radium-226, lead-210, thorium-232, radium-228, thorium-228, uranium-235, protactinium-231, actinium-227, plutonium-241, americium-241, neptunium-237, uranium-233, thorium-229, cobalt-57, cobalt-60, cesium-134, cesium-137, europium-152, europium-154, and iridium-192. These are the same radionuclides as used in the gross alpha/beta calculations.

Table A.1 shows how the dose for each of the three pathways increases with an increase of contaminated area.

Table A 1: Dose (mrem/y) as a Function of Area

Area (m^2)	External	Inhalation	Ingestion
1	6.679E+00	6.835E-01	5.815E-03
10	3.072E+01	8.785E-01	5.815E-02
100	5.250E+01	1.126E+00	5.815E-01
1000	5.945E+01	1.436E+00	5.815E+00
10000	6.245E+01	1.824E+00	5.815E+00
100000	6.504E+01	2.301E+00	5.815E+00
1000000	6.627E+01	2.881E+00	5.815E+00
10000000	6.627E+01	3.575E+00	5.815E+00
100000000	6.627E+01	4.387E+00	5.815E+00
1000000000	6.627E+01	5.317E+00	5.815E+00
10000000000	6.627E+01	6.352E+00	5.815E+00

Table A.2 shows the contribution (as a percentage) each exposure pathway has to the total dose for Table A.1.

Table A 2: Fraction of Total Dose due to Variations in Area

Area (m^2)	External	Inhalation	Ingestion
1	90.64%	9.28%	0.08%
10	97.04%	2.78%	0.18%
100	96.85%	2.08%	1.07%
1000	89.13%	2.15%	8.72%
10000	89.10%	2.60%	8.30%
100000	88.91%	3.15%	7.95%
1000000	88.40%	3.84%	7.76%
10000000	87.59%	4.73%	7.69%
100000000	86.66%	5.74%	7.60%
1000000000	85.62%	6.87%	7.51%
10000000000	84.49%	8.10%	7.41%

Table A.3 shows how the dose for each of the three pathways increases with an increase of contaminated soil thickness.

Table A 3: Dose (mrem/y) as a Function of Thickness

Thickness (m)	External	Inhalation	Ingestion
0.1	4.522E+01	1.159E+00	3.717E+00
0.2	5.680E+01	1.786E+00	5.712E+00
0.3	5.993E+01	1.800E+00	5.749E+00
0.4	6.062E+01	1.807E+00	5.768E+00
0.5	6.055E+01	1.811E+00	5.780E+00
0.6	6.088E+01	1.814E+00	5.788E+00
0.7	6.112E+01	1.816E+00	5.793E+00
0.8	6.131E+01	1.817E+00	5.797E+00
0.9	6.147E+01	1.818E+00	5.800E+00
1	6.162E+01	1.819E+00	5.803E+00
1.1	6.174E+01	1.820E+00	5.805E+00
1.2	6.186E+01	1.821E+00	5.807E+00
1.3	6.196E+01	1.821E+00	5.808E+00
1.4	6.205E+01	1.822E+00	5.810E+00
1.5	6.213E+01	1.822E+00	5.811E+00
2	6.245E+01	1.824E+00	5.815E+00
2.5	6.267E+01	1.824E+00	5.817E+00
3	6.283E+01	1.825E+00	5.819E+00

Due to erosion, RESRAD calculates several dose rates during an exposure period. As a conservative approximation, the only dose rate used in this study is the maximum dose rate, which occurs at the beginning of the exposure period.

Table A.4 shows the contribution (as a percentage) each exposure pathway has to the total dose for Table A.3.

Table A 4: Fraction of Total Dose due to Variations in Thickness

Thickness (m)	External	Inhalation	Ingestion
0.1	90.27%	2.31%	7.42%
0.2	88.34%	2.78%	8.88%
0.3	88.81%	2.67%	8.52%
0.4	88.89%	2.65%	8.46%
0.5	88.86%	2.66%	8.48%
0.6	88.90%	2.65%	8.45%
0.7	88.93%	2.64%	8.43%
0.8	88.95%	2.64%	8.41%
0.9	88.97%	2.63%	8.40%
1	88.99%	2.63%	8.38%
1.1	89.01%	2.62%	8.37%
1.2	89.02%	2.62%	8.36%
1.3	89.04%	2.62%	8.35%
1.4	89.05%	2.61%	8.34%
1.5	89.06%	2.61%	8.33%
2	89.10%	2.60%	8.30%
2.5	89.13%	2.59%	8.27%
5	89.15%	2.59%	8.26%

Appendix B: RESRAD Data for Linearity between Concentration and Dose Rate

Below are dose rates calculated by RESRAD for concentrations of 1 pCi/g of each of the listed radionuclides and 50 pCi/g of each of the listed radionuclides. The multiplier of 50 was used because it was the reference concentration multiplied by an integer (5) and an order of magnitude (10). This analysis made use of the parameters listed in the "RESRAD Input Parameters" section.

Table B 1: Total Dose Rate (mrem/y) from RESRAD

Radionuclide	1 pCi/g	50 pCi/g
U-238	1.823E-01	9.113E+00
U-234	5.847E-02	2.923E+00
Th-230	1.305E-01	6.527E+00
Ra-226	9.623E+00	4.812E+02
Pb-210	7.966E-01	3.983E+01
Th-232	9.981E-01	4.991E+01
Ra-228	6.281E+00	3.140E+02
Th-228	7.382E+00	3.691E+02
U-235	6.963E-01	3.482E+01
Pa-231	1.661E+00	8.301E+01
Ac-227	4.610E+00	2.305E+02
Pu-241	9.435E-03	4.718E-01
Am-241	5.243E-01	2.621E+01
Np-237	1.532E+00	7.661E+01
U-233	6.069E-02	3.034E+00
Th-229	2.247E+00	1.123E+02
Co-57	2.766E-01	1.382E+01
Co-60	1.290E+01	6.451E+02
Cs-134	6.844E+00	3.421E+02
Cs-137	2.871E+00	1.436E+02
Eu-152	5.797E+00	2.898E+02
Eu-154	6.269E+00	3.135E+02
Ir-192	2.308E+00	1.154E+02

To compare the linearity of dose rate with increasing concentration, the 1 pCi/g results were multiplied by 50 to get a "calculated" result for dose rates at

50 pCi/g. The calculated results (shown in Table B.2) were compared to the actual results (shown in Table B.1).

Table B 2: Linearity Comparison

Radionuclide	1 pCi/g Results Times 50	Ratio of 50 pCi/g Results
U-238	9.115E+00	1.000
U-234	2.924E+00	1.000
Th-230	6.527E+00	1.000
Ra-226	4.812E+02	1.000
Pb-210	3.983E+01	1.000
Th-232	4.991E+01	1.000
Ra-228	3.140E+02	1.000
Th-228	3.691E+02	1.000
U-235	3.481E+01	1.000
Pa-231	8.303E+01	1.000
Ac-227	2.305E+02	1.000
Pu-241	4.717E-01	1.000
Am-241	2.621E+01	1.000
Np-237	7.661E+01	1.000
U-233	3.034E+00	1.000
Th-229	1.123E+02	1.000
Co-57	1.383E+01	1.000
Co-60	6.451E+02	1.000
Cs-134	3.422E+02	1.000
Cs-137	1.436E+02	1.000
Eu-152	2.898E+02	1.000
Eu-154	3.135E+02	1.000
Ir-192	1.154E+02	1.000

Therefore, the relationship between dose rate and radionuclide concentration is linear. This was not surprising given that dose conversion factors (DCFs) are used in RESRAD to obtain a dose rate. These DCFs were calculated in units mrem/y per pCi/g, which implies a linear relationship due to unit analysis.

Appendix C: RESRAD Printouts

The following values were used in the example RESRAD printouts of this appendix:

Fraction of time spent indoors: 0.5 (default parameter)

Fraction of time spent outdoors: 0.5

Area of contaminated zone: 1,000,000 m^2

Thickness of contaminated zone: 1 m

Cover Depth: 0 m (default parameter)

Soil ingestion: 110 g/y

Inhalation rate: 13,000 m3/y

Pathways used: External gamma, inhalation, soil ingestion

Radionuclides entered: 1 pCi/g of americium-241, 1 pCi/g of cobalt-60, 1 pCi/g of europium-152, 1 pCi/g of radium-226, 1 pCi/g of thorium-232, 1 pCi/g of uranium-235, 1 pCi/g of uranium-238

Default parameters were used for all variables not listed above.

Table of Contents

Part I: Mixture Sums and Single Radionuclide Guidelines

Dose Conversion Factor (and Related) Parameter Summary
File: FGR 13 MORBIDITY

Menu	Parameter	Current Value	Base Case*	Parameter Name
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Ac-227+D	6.724E+00	6.700E+00	DCF2(1)
B-1	Am-241	4.440E-01	4.440E-01	DCF2(2)
B-1	Co-60	2.190E-04	2.190E-04	DCF2(3)
B-1	Eu-152	2.210E-04	2.210E-04	DCF2(4)
B-1	Gd-152	2.430E-01	2.430E-01	DCF2(6)
B-1	Np-237+D	5.400E-01	5.400E-01	DCF2(7)
B-1	Pa-231	1.280E+00	1.280E+00	DCF2(8)
B-1	Pb-210+D	1.380E-02	1.360E-02	DCF2(9)
B-1	Po-210	9.400E-03	9.400E-03	DCF2(10)
B-1	Ra-226+D	8.594E-03	8.580E-03	DCF2(11)
B-1	Ra-228+D	5.078E-03	4.770E-03	DCF2(12)
B-1	Th-228+D	3.454E-01	3.420E-01	DCF2(13)
B-1	Th-229+D	2.169E+00	2.150E+00	DCF2(14)
B-1	Th-230	3.260E-01	3.260E-01	DCF2(15)
B-1	Th-232	1.640E+00	1.640E+00	DCF2(16)
B-1	U-233	1.350E-01	1.350E-01	DCF2(17)
B-1	U-234	1.320E-01	1.320E-01	DCF2(18)
B-1	U-235+D	1.230E-01	1.230E-01	DCF2(19)
B-1	U-238	1.180E-01	1.180E-01	DCF2(20)
B-1	U-238+D	1.180E-01	1.180E-01	DCF2(21)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Ac-227+D	1.480E-02	1.410E-02	DCF3(1)
D-1	Am-241	3.640E-03	3.640E-03	DCF3(2)
D-1	Co-60	2.690E-05	2.690E-05	DCF3(3)
D-1	Eu-152	6.480E-06	6.480E-06	DCF3(4)
D-1	Gd-152	1.610E-04	1.610E-04	DCF3(6)

Dose Conversion Factor (and Related) Parameter Summary (continued)
File: FGR 13 MORBIDITY

Menu	Parameter	Current Value	Base Case*	Parameter Name
D-34	Am-241 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(2,1)
D-34	Am-241 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-05	5.000E-05	RTF(2,2)
D-34	Am-241 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	2.000E-06	2.000E-06	RTF(2,3)
D-34				
D-34	Co-60 , plant/soil concentration ratio, dimensionless	8.000E-02	8.000E-02	RTF(3,1)
D-34	Co-60 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-02	2.000E-02	RTF(3,2)
D-34	Co-60 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	2.000E-03	2.000E-03	RTF(3,3)
D-34				
D-34	Eu-152 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(4,1)
D-34	Eu-152 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(4,2)
D-34	Eu-152 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-05	5.000E-05	RTF(4,3)
D-34				
D-34	Gd-152 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(6,1)
D-34	Gd-152 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(6,2)
D-34	Gd-152 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	2.000E-05	2.000E-05	RTF(6,3)
D-34				
D-34	Np-237+D , plant/soil concentration ratio, dimensionless	2.000E-02	2.000E-02	RTF(7,1)
D-34	Np-237+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(7,2)
D-34	Np-237+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	Pa-231 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(8,1)
D-34	Pa-231 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(8,2)
D-34	Pa-231 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(8,3)
D-34				
D-34	Pb-210+D , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(9,1)
D-34	Pb-210+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(9,2)
D-34	Pb-210+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(9,3)
D-34				
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(10,1)

Dose Conversion Factor (and Related) Parameter Summary (continued)
File: FGR 13 MORBIDITY

Menu	Parameter		Current Value	Base Case*	Parameter Name
D-34	Th-232	, plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(16,1)
D-34	Th-232	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(16,2)
D-34	Th-232	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(16,3)
D-34					
D-34	U-233	, plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(17,1)
D-34	U-233	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(17,2)
D-34	U-233	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(17,3)
D-34					
D-34	U-234	, plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(18,1)
D-34	U-234	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(18,2)
D-34	U-234	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(18,3)
D-34					
D-34	U-235+D	, plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(19,1)
D-34	U-235+D	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(19,2)
D-34	U-235+D	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(19,3)
D-34					
D-34	U-238	, plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(20,1)
D-34	U-238	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(20,2)
D-34	U-238	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(20,3)
D-34					
D-34	U-238+D	, plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(21,1)
D-34	U-238+D	, beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(21,2)
D-34	U-238+D	, milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(21,3)
D-5	Bioaccumulation factors, fresh water, L/kg:				
D-5	Ac-227+D	, fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Ac-227+D	, crustacea and mollusks	1.000E+03	1.000E+03	BIOFAC(1,2)
D-5					
D-5	Am-241	, fish	3.000E+01	3.000E+01	BIOFAC(2,1)

Dose Conversion Factor (and Related) Parameter Summary (continued)
File: FGR 13 MORBIDITY

Menu	Parameter	Current Value	Base Case*	Parameter Name
D-5	Ra-226+D , fish	5.000E+01	5.000E+01	BIOFAC(11,1)
D-5	Ra-226+D , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(11,2)
D-5				
D-5	Ra-228+D , fish	5.000E+01	5.000E+01	BIOFAC(12,1)
D-5	Ra-228+D , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(12,2)
D-5				
D-5	Th-228+D , fish	1.000E+02	1.000E+02	BIOFAC(13,1)
D-5	Th-228+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(13,2)
D-5				
D-5	Th-229+D , fish	1.000E+02	1.000E+02	BIOFAC(14,1)
D-5	Th-229+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(14,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(15,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(15,2)
D-5				
D-5	Th-232 , fish	1.000E+02	1.000E+02	BIOFAC(16,1)
D-5	Th-232 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(16,2)
D-5				

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.000E+06	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	1.000E+00	2.000E+00	---	THICK0
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	3.000E+00	3.000E+00	---	T(3)
R011	Times for calculations (yr)	1.000E+01	1.000E+01	---	T(4)
R011	Times for calculations (yr)	3.000E+01	3.000E+01	---	T(5)
R011	Times for calculations (yr)	1.000E+02	1.000E+02	---	T(6)
R011	Times for calculations (yr)	3.000E+02	3.000E+02	---	T(7)
R011	Times for calculations (yr)	1.000E+03	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Am-241	1.000E+00	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Co-60	1.000E+00	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Eu-152	1.000E+00	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.000E+00	0.000E+00	---	S1(11)
R012	Initial principal radionuclide (pCi/g): Th-232	1.000E+00	0.000E+00	---	S1(16)
R012	Initial principal radionuclide (pCi/g): U-235	1.000E+00	0.000E+00	---	S1(19)
R012	Initial principal radionuclide (pCi/g): U-238	1.000E+00	0.000E+00	---	S1(20)
R012	Concentration in groundwater (pCi/L): Am-241	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Co-60	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Eu-152	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(11)
R012	Concentration in groundwater (pCi/L): Th-232	not used	0.000E+00	---	W1(16)
R012	Concentration in groundwater (pCi/L): U-235	not used	0.000E+00	---	W1(19)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(20)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Am-241				
R016	Contaminated zone (cm**3/g)	2.000E+01	2.000E+01	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	2.000E+01	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	2.000E+01	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.649E-02	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Co-60				

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Th-232				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(16)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(16,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(16)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	5.556E-06	ALEACH(16)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(16)
R016	Distribution coefficients for U-235				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(19)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(19,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(19)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.638E-03	ALEACH(19)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(19)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(20)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(20,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(20)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.638E-03	ALEACH(20)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(20)
R016	Distribution coefficients for daughter Ac-227				
R016	Contaminated zone (cm**3/g)	2.000E+01	2.000E+01	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	2.000E+01	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	2.000E+01	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.649E-02	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for daughter Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.328E-03	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R016	Distribution coefficients for daughter Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(10)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(10,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(10)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.264E-02	ALEACH(10)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(10)
R016	Distribution coefficients for daughter Ra-228				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(12)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(12,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(12)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	4.747E-03	ALEACH(12)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(12)
R016	Distribution coefficients for daughter Th-228				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(13)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(13,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(13)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	5.556E-06	ALEACH(13)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(13)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for daughter U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(18)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(18,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(18)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.638E-03	ALEACH(18)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(18)
R017	Inhalation rate (m**3/yr)	1.300E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	1.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	3.000E+01	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	5.000E-01	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	5.000E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	1.000E+00	1.000E+00	>0 shows circular AREA.	FS
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	not used	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	not used	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	not used	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	not used	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	not used	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	not used	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	not used	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	not used	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	not used	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	not used	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	not used	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	not used	0.000E+00	---	RAD_SHAPE(12)
R018	Fractions of annular areas within AREA:				

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS

Contaminated Zone Dimensions		Initial Soil Concentrations, pCi/g	
Area:	1000000.00 square meters	Am-241	1.000E+00
Thickness:	1.00 meters	Co-60	1.000E+00
Cover Depth:	0.00 meters	Eu-152	1.000E+00
		Ra-226	1.000E+00
		Th-232	1.000E+00
		U-235	1.000E+00
		U-238	1.000E+00

Total Dose TDOSE(t), mrem/yr

Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	3.682E-02	0.0012	1.071E-01	0.0035	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.968E-01	0.0129
Co-60	1.290E+01	0.4187	4.994E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.772E-03	0.0001
Eu-152	5.794E+00	0.1881	5.241E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.944E-04	0.0000
Ra-226	9.464E+00	0.3072	2.152E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.553E-01	0.0050
Th-232	3.498E-01	0.0114	3.998E-01	0.0130	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.100E-01	0.0101
U-235	6.417E-01	0.0208	2.984E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.932E-02	0.0010
U-238	1.286E-01	0.0042	2.864E-02	0.0009	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.946E-02	0.0010
Total	2.932E+01	0.9516	5.677E-01	0.0184	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.244E-01	0.0300

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	3.616E-02	0.0012	1.052E-01	0.0035	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.897E-01	0.0131
Co-60	1.131E+01	0.3803	4.377E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.430E-03	0.0001
Eu-152	5.500E+00	0.1850	4.973E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.590E-04	0.0000
Ra-226	9.415E+00	0.3167	2.296E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.771E-01	0.0060
Th-232	1.177E+00	0.0396	4.027E-01	0.0135	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.299E-01	0.0111
U-235	6.375E-01	0.0214	2.945E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.916E-02	0.0010
U-238	1.277E-01	0.0043	2.945E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.927E-02	0.0010
Total	2.820E+01	0.9486	5.684E-01	0.0191	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.502E-01	0.0322

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	3.488E-02	0.0012	1.014E-01	0.0036	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.758E-01	0.0132
Co-60	8.686E+00	0.3055	3.363E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.867E-03	0.0001
Eu-152	4.953E+00	0.1742	4.479E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.934E-04	0.0000
Ra-226	9.310E+00	0.3277	2.590E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.205E-01	0.0078
Th-232	3.087E+00	0.1086	4.128E-01	0.0145	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.684E-01	0.0130
U-235	6.291E-01	0.0221	2.928E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.882E-02	0.0010
U-238	1.260E-01	0.0044	2.807E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.888E-02	0.0010
Total	2.683E+01	0.9438	5.743E-01	0.0202	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.025E+00	0.0360

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+00 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+01 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	3.073E-02	0.0011	8.938E-02	0.0033	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.311E-01	0.0123
Co-60	3.452E+00	0.1279	1.336E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.416E-04	0.0000
Eu-152	3.432E+00	0.1272	3.103E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.112E-04	0.0000
Ra-226	8.987E+00	0.3330	3.448E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.474E-01	0.0129
Th-232	8.572E+00	0.3176	4.487E-01	0.0166	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.634E-01	0.0172
U-235	6.006E-01	0.0223	2.804E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.772E-02	0.0010
U-238	1.203E-01	0.0045	2.680E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.757E-02	0.0010
Total	2.519E+01	0.9335	5.964E-01	0.0221	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.198E+00	0.0444

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+01 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+01 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	2.140E-02	0.0009	6.224E-02	0.0025	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.304E-01	0.0092
Co-60	2.471E-01	0.0099	9.568E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.311E-05	0.0000
Eu-152	1.203E+00	0.0482	1.088E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.442E-04	0.0000
Ra-226	8.104E+00	0.3245	4.779E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.499E-01	0.0220
Th-232	1.281E+01	0.5129	4.785E-01	0.0192	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.322E-01	0.0213
U-235	5.262E-01	0.0211	2.490E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.492E-02	0.0010
U-238	1.053E-01	0.0042	2.347E-02	0.0009	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.414E-02	0.0010
Total	2.302E+01	0.9217	5.939E-01	0.0238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.362E+00	0.0545

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+01 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)

As mrem/yr and Fraction of Total Dose At t = 1.000E+02 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	6.042E-03	0.0003	1.754E-02	0.0008	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.498E-02	0.0031
Co-60	2.427E-05	0.0000	9.396E-11	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.216E-09	0.0000
Eu-152	3.071E-02	0.0015	2.777E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.680E-06	0.0000
Ra-226	5.640E+00	0.2684	4.600E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.633E-01	0.0268
Th-232	1.319E+01	0.6281	4.810E-01	0.0229	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.382E-01	0.0256
U-235	3.317E-01	0.0158	1.675E-02	0.0008	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.740E-02	0.0008
U-238	6.619E-02	0.0032	1.475E-02	0.0007	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.517E-02	0.0007
Total	1.926E+01	0.9174	5.346E-01	0.0255	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.199E+00	0.0571

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)

As mrem/yr and Fraction of Total Dose At t = 1.000E+02 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+02 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	1.738E-04	0.0000	4.720E-04	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.749E-03	0.0001
Co-60	8.587E-17	0.0000	3.326E-22	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.046E-20	0.0000
Eu-152	8.621E-07	0.0000	7.798E-12	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.033E-10	0.0000
Ra-226	2.001E+00	0.1211	1.699E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.094E-01	0.0127
Th-232	1.317E+01	0.7968	4.805E-01	0.0291	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.376E-01	0.0325
U-235	8.877E-02	0.0054	5.334E-03	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.993E-03	0.0004
U-238	1.755E-02	0.0011	3.912E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.025E-03	0.0002
Total	1.527E+01	0.9243	4.919E-01	0.0298	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.587E-01	0.0459

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 3.000E+02 years

Water Dependent Pathways

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+03 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Am-241	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Eu-152	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Th-232	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-235	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+03 years

Water Dependent Pathways

Dose/Source Ratios Summed Over All Pathways

Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years (mrem/yr)/(pCi/g) 0.000E+00	1.000E+00	3.000E+00	1.000E+01	3.000E+01	1.000E+02	3.000E+02	1.000E+03
Am-241	Am-241	1.000E+00	5.407E-01	5.310E-01	5.122E-01	4.512E-01	3.142E-01	8.854E-02	2.374E-03	0.000E+00
Am-241	Np-237+D	1.000E+00	2.500E-07	7.434E-07	1.702E-06	4.778E-06	1.154E-05	2.144E-05	2.017E-05	0.000E+00
Am-241	U-233	1.000E+00	1.544E-14	1.073E-13	5.577E-13	4.699E-12	3.348E-11	2.009E-10	4.987E-10	0.000E+00
Am-241	Th-229+D	1.000E+00	1.291E-17	1.925E-16	2.218E-15	5.625E-14	1.212E-12	2.866E-11	2.875E-10	0.000E+00
Am-241	∑DSR(j)		5.407E-01	5.310E-01	5.122E-01	4.512E-01	3.142E-01	8.857E-02	2.394E-03	0.000E+00
Co-60	Co-60	1.000E+00	1.290E+01	1.131E+01	8.687E+00	3.452E+00	2.472E-01	2.427E-05	8.509E-17	0.000E+00
Eu-152	Eu-152	7.208E-01	4.178E+00	3.965E+00	3.570E+00	2.474E+00	8.475E-01	2.214E-02	6.215E-07	0.000E+00
Eu-152	Eu-152	2.792E-01	1.618E+00	1.536E+00	1.383E+00	9.583E-01	3.360E-01	8.576E-03	2.407E-07	0.000E+00
Eu-152	Gd-152	2.792E-01	6.767E-17	1.983E-16	4.398E-16	1.109E-15	2.080E-15	2.530E-15	2.346E-15	0.000E+00
Eu-152	∑DSR(j)		1.618E+00	1.536E+00	1.383E+00	9.583E-01	3.340E-01	8.576E-03	2.407E-07	0.000E+00
Ra-226+D	Ra-226+D	1.000E+00	9.611E+00	9.561E+00	9.463E+00	9.124E+00	8.227E+00	5.725E+00	2.031E+00	0.000E+00
Ra-226+D	Pb-210+D	1.000E+00	9.201E-03	2.712E-02	6.089E-02	1.597E-01	3.213E-01	3.509E-01	1.345E-01	0.000E+00
Ra-226+D	Po-210	1.000E+00	1.319E-03	6.301E-03	1.800E-02	5.294E-02	1.103E-01	1.245E-01	4.467E-02	0.000E+00
Ra-226+D	∑DSR(j)		9.621E+00	9.595E+00	9.541E+00	9.338E+00	8.659E+00	6.208E+00	2.212E+00	0.000E+00
Th-232	Th-232	1.000E+00	6.999E-01	6.999E-01	6.999E-01	6.999E-01	6.998E-01	6.996E-01	6.988E-01	0.000E+00
Th-232	Ra-228+D	1.000E+00	3.028E-01	8.605E-01	1.786E+00	3.685E+00	4.927E+00	5.035E+00	5.029E+00	0.000E+00
Th-232	Th-228+D	1.000E+00	5.691E-02	3.487E-01	1.382E+00	5.099E+00	8.194E+00	8.474E+00	8.457E+00	0.000E+00
Th-232	∑DSR(j)		1.060E+00	1.909E+00	3.868E+00	9.484E+00	1.382E+01	1.421E+01	1.419E+01	0.000E+00

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Summary : RESRAD Default Parameters   File: Site7.RAD

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00	3.000E+00	1.000E+01	3.000E+01	1.000E+02	3.000E+02	1.000E+03
Am-241	4.623E+01	4.708E+01	4.881E+01	5.540E+01	7.956E+01	2.823E+02	1.044E+04	*3.431E+12
Co-60	1.939E+00	2.211E+00	2.876E+00	7.242E+00	1.011E+02	1.030E+06	*1.132E+15	*1.132E+15
Eu-152	4.313E+00	4.545E+00	5.047E+00	7.283E+00	2.077E+01	8.139E+02	2.899E+07	*1.765E+14
Ra-226	2.598E+00	2.606E+00	2.620E+00	2.677E+00	2.887E+00	4.027E+00	1.130E+01	*9.885E+11
Th-232	2.359E+01	1.310E+01	6.463E+00	2.636E+00	1.809E+00	1.759E+00	1.762E+00	*1.097E+05
U-235	3.567E+01	3.590E+01	3.638E+01	3.809E+01	4.340E+01	6.834E+01	2.498E+02	*2.141E+06
U-238	1.339E+02	1.348E+02	1.366E+02	1.431E+02	1.635E+02	2.601E+02	9.810E+02	*3.361E+05

*At specific activity limit

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00	3.000E+00	1.000E+01	3.000E+01	1.000E+02	3.000E+02	1.000E+03
Am-241	Am-241	1.000E+00	5.407E-01	5.310E-01	5.122E-01	4.512E-01	3.142E-01	8.854E-02	2.374E-03	0.000E+00
Np-237	Am-241	1.000E+00	2.500E-07	7.434E-07	1.702E-06	4.778E-06	1.154E-05	2.144E-05	2.017E-05	0.000E+00
U-233	Am-241	1.000E+00	1.544E-14	1.073E-13	5.577E-13	4.699E-12	3.348E-11	2.089E-10	4.987E-10	0.000E+00
Th-229	Am-241	1.000E+00	1.291E-17	1.925E-16	2.218E-15	5.625E-14	1.212E-12	2.866E-11	2.875E-10	0.000E+00
Co-60	Co-60	1.000E+00	1.290E+01	1.131E+01	8.687E+00	3.452E+00	2.472E-01	2.427E-05	8.589E-17	0.000E+00
Eu-152	Eu-152	7.208E-01	4.178E+00	3.965E+00	3.570E+00	2.474E+00	8.675E-01	2.214E-02	6.215E-07	0.000E+00
Eu-152	Eu-152	2.792E-01	1.618E+00	1.536E+00	1.383E+00	9.583E-01	3.360E-01	8.576E-03	2.407E-07	0.000E+00
Eu-152	∑DOSE(j)		5.797E+00	5.501E+00	4.953E+00	3.432E+00	1.203E+00	3.071E-02	8.622E-07	0.000E+00
Gd-152	Eu-152	2.792E-01	6.767E-17	1.983E-16	4.398E-16	1.109E-15	2.080E-15	2.530E-15	2.346E-15	0.000E+00
Ra-226	Ra-226	1.000E+00	9.611E+00	9.561E+00	9.463E+00	9.126E+00	8.227E+00	5.725E+00	2.031E+00	0.000E+00
Ra-226	U-238	9.999E-01	4.422E-15	6.607E-14	7.640E-13	1.962E-11	4.379E-10	1.142E-08	1.293E-07	0.000E+00
Ra-226	∑DOSE(j)		9.611E+00	9.561E+00	9.463E+00	9.126E+00	8.227E+00	5.725E+00	2.031E+00	0.000E+00
Pb-210	Ra-226	1.000E+00	9.201E-03	2.712E-02	6.089E-02	1.597E-01	3.213E-01	3.509E-01	1.345E-01	0.000E+00
Pb-210	U-238	9.999E-01	1.703E-18	5.231E-17	1.292E-15	9.395E-14	5.445E-12	3.368E-10	6.078E-09	0.000E+00
Pb-210	∑DOSE(j)		9.201E-03	2.712E-02	6.089E-02	1.597E-01	3.213E-01	3.509E-01	1.345E-01	0.000E+00
Po-210	Ra-226	1.000E+00	1.319E-03	6.301E-03	1.800E-02	5.294E-02	1.103E-01	1.245E-01	4.667E-02	0.000E+00
Po-210	U-238	9.999E-01	1.438E-19	7.315E-18	2.696E-16	2.692E-14	1.767E-12	1.146E-10	2.096E-09	0.000E+00
Po-210	∑DOSE(j)		1.319E-03	6.301E-03	1.800E-02	5.294E-02	1.103E-01	1.245E-01	4.667E-02	0.000E+00

Individual Nuclide Soil Concentration

Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00	3.000E+00	1.000E+01	3.000E+01	1.000E+02	3.000E+02	1.000E+03
Am-241	Am-241	1.000E+00	1.000E+00	9.821E-01	9.472E-01	8.345E-01	5.411E-01	1.630E-01	4.391E-03	1.386E-08
Np-237	Am-241	1.000E+00	0.000E+00	3.208E-07	9.439E-07	2.943E-06	7.342E-06	1.370E-05	1.298E-05	5.285E-06
U-233	Am-241	1.000E+00	0.000E+00	7.021E-13	6.211E-12	6.490E-11	4.940E-10	3.154E-09	7.572E-09	4.291E-09
Th-229	Am-241	1.000E+00	0.000E+00	2.215E-17	5.903E-16	2.009E-14	4.970E-13	1.216E-11	1.232E-10	5.196E-10
Co-60	Co-60	1.000E+00	1.000E+00	8.765E-01	6.733E-01	2.676E-01	1.916E-02	1.881E-06	6.659E-18	0.000E+00
Eu-152	Eu-152	7.208E-01	7.208E-01	6.840E-01	6.159E-01	4.268E-01	1.496E-01	3.819E-03	1.072E-07	1.257E-23
Eu-152	Eu-152	2.792E-01	2.792E-01	2.649E-01	2.386E-01	1.653E-01	5.796E-02	1.479E-03	4.153E-08	4.870E-24
Eu-152	ΣS(j):		1.000E+00	9.489E-01	8.545E-01	5.921E-01	2.076E-01	5.299E-03	1.488E-07	1.744E-23
Gd-152	Eu-152	2.792E-01	0.000E+00	1.745E-15	4.971E-15	1.392E-14	2.489E-14	3.291E-14	3.053E-14	2.301E-14
Ra-226	Ra-226	1.000E+00	1.000E+00	9.948E-01	9.846E-01	9.495E-01	8.561E-01	5.957E-01	2.114E-01	5.625E-03
Ra-226	U-238	9.999E-01	0.000E+00	1.834E-15	4.906E-14	1.759E-12	4.334E-11	1.170E-09	1.338E-08	4.514E-08
Ra-226	ΣS(j):		1.000E+00	9.948E-01	9.846E-01	9.495E-01	8.561E-01	5.957E-01	2.114E-01	5.625E-03
Pb-210	Ra-226	1.000E+00	0.000E+00	3.047E-02	8.790E-02	2.559E-01	5.316E-01	5.994E-01	2.247E-01	5.981E-03
Pb-210	U-238	9.999E-01	0.000E+00	1.417E-17	1.124E-15	1.290E-13	8.534E-12	5.527E-10	1.010E-08	4.042E-08
Pb-210	ΣS(j):		0.000E+00	3.047E-02	8.790E-02	2.559E-01	5.316E-01	5.994E-01	2.247E-01	5.981E-03
Po-210	Ra-226	1.000E+00	0.000E+00	1.644E-02	7.155E-02	2.403E-01	5.177E-01	5.900E-01	2.214E-01	5.893E-03
Po-210	U-238	9.999E-01	0.000E+00	3.926E-18	6.149E-16	1.039E-13	7.054E-12	5.340E-10	9.805E-09	3.971E-08
Po-210	ΣS(j):		0.000E+00	1.644E-02	7.155E-02	2.403E-01	5.177E-01	5.900E-01	2.214E-01	5.893E-03
Th-232	Th-232	1.000E+00	1.000E+00	1.000E+00	1.000E+00	9.999E-01	9.998E-01	9.994E-01	9.983E-01	9.945E-01

Appendix D: Total Dose per pCi/g of Long-lived Isotopes Common in Reactor Products, Accelerators, and Nuclear Medicine

Table D.1 shows the total dose rate per 1 pCi/g of various radionuclides. These radionuclides are common in reactors, nuclear medicine, and accelerators. The dose rate per alpha is equal to the total dose rate per concentration divided by the alpha emissions per decay. Similarly, the dose rate per beta is equal to the total dose rate per concentration divided by the beta emissions per decay. Isotopes that decay by electron capture (EC) do not have a dose rate per alpha or beta.

For radionuclides in one of the four series, the decay of a long-lived radionuclide includes particles emitted by short-lived (half-life less than 30 days) radionuclides following in the chain. For example, the decay of uranium-238 includes the decay of thorium-234 and protactinium-234m, so a single decay of uranium-238 emits one alpha particle and two beta particles.

Table D 1: Dose Rates per 1 pCi/g Concentration

Radionuclide	Series	Dose Rate (mrem/y)	Alpha Emissions per Decay	Beta Emissions per Decay	Dose Rate Indicated By 1 pCi_{α}/g (mrem/y)	Dose Rate Indicated By 1 pCi_{β}/g (mrem/y)
H-3	None	3.490E-03	0	1	N/A	3.490E-03
Be-7	None	5.103E-02	EC	EC	N/A	N/A
Be-10	None	1.513E-03	0	1	N/A	1.513E-03
C-14	None	1.497E-03	0	1	N/A	1.497E-03
Na-22	None	1.004E+01	0	0.898	N/A	1.118E+01
Al-26	None	7.483E+00	0	0.818	N/A	9.148E+00
Cl-36	None	1.461E-03	EC	EC	N/A	N/A
K-40	None	8.603E-01	0	0.893	N/A	9.634E-01
Sc-46	None	2.330E+00	0	1	N/A	2.330E+00
Mn-54	None	3.001E+00	0	EC	N/A	N/A
Fe-55	None	5.946E-05	0	EC	N/A	N/A

Radionuclide	Series	Dose Rate (mrem/y)	Alpha Emissions per Decay	Beta Emissions per Decay	Dose Rate Indicated By 1 pCi_{α}/g (mrem/y)	Dose Rate Indicated By 1 pCi_{β}/g (mrem/y)
Co-56	None	5.960E+00	EC	EC	N/A	N/A
Co-57	None	2.765E-01	EC	EC	N/A	N/A
Co-58	None	1.377E+00	EC	EC	N/A	N/A
Fe-59	None	1.137E+00	0	0.999	N/A	1.138E+00
Co-60	None	1.290E+01	0	1	N/A	1.290E+01
Ni-63	None	6.476E-05	0	1	N/A	6.476E-05
Zn-65	None	1.120E+00	EC	EC	N/A	N/A
Se-75	None	4.471E-01	EC	EC	N/A	N/A
Sr-85	None	6.320E-01	EC	EC	N/A	N/A
Rb-87	None	6.608E-04	0	1	N/A	6.608E-04
Y-88	None	5.756E+00	EC	EC	N/A	N/A
Sr-89	None	1.729E-03	0	1	N/A	1.729E-03
Sr-90	None	3.739E-02	0	1	N/A	3.739E-02
Zr-93	None	2.632E-04	0	1	N/A	2.632E-04
Zr-95	None	1.752E+00	0	1	N/A	1.752E+00
Ru-106	None	4.380E-01	0	1	N/A	4.380E-01
Cd-109	None	5.828E-03	EC	EC	N/A	N/A
Ag-110m	None	5.243E+00	0	0.985	N/A	5.323E+00
Sb-124	None	1.720E+00	0	1	N/A	1.720E+00
I-125	None	3.456E-03	EC	EC	N/A	N/A
Sb-125	None	9.628E-01	0	1	N/A	9.628E-01
I-129	None	2.551E-02	0	1	N/A	2.551E-02
Cs-134	None	6.843E+00	0	1	N/A	6.843E+00
Cs-135	None	8.113E-04	0	1	N/A	8.113E-04
Cs-137	None	2.872E+00	0	1	N/A	2.872E+00
Ce-139	None	2.476E-01	EC	EC	N/A	N/A
Ce-141	None	3.469E-02	0	1	N/A	3.469E-02
Ce-144	None	1.838E-01	0	1	N/A	1.838E-01
Pm-147	None	1.473E-04	0	1	N/A	1.473E-04
Eu-152	None	5.797E+00	0	0.279	N/A	2.078E+01
Gd-153	None	1.290E-01	EC	EC	N/A	N/A
Eu-154	None	6.269E+00	0	1	N/A	6.269E+00
Yb-169	None	1.187E-01	EC	EC	N/A	N/A
Ta-182	None	1.752E+00	0	0.99	N/A	1.770E+00
Ir-192	None	7.825E-01	0	0.958	N/A	8.168E-01
Hg-203	None	1.967E-01	0	1	N/A	1.967E-01
Tl-204	None	1.807E-03	0	0.974	N/A	1.855E-03
Bi-207	None	4.009E+00	EC	EC	N/A	N/A
Pu-238	None	4.457E-01	1	0	4.457E-01	N/A
Pu-239	None	4.940E-01	1	0	4.940E-01	N/A
Pu-240	None	4.939E-01	1	0	4.939E-01	N/A

Radionuclide	Series	Dose Rate (mrem/y)	Alpha Emissions per Decay	Beta Emissions per Decay	Dose Rate Indicated By 1 pCi_{α}/g (mrem/y)	Dose Rate Indicated By 1 pCi_{β}/g (mrem/y)
U-238	Uranium	1.867E-01	1	2	1.867E-01	9.335E-02
U-234	Uranium	6.339E-02	1	0	6.339E-02	N/A
Th-230	Uranium	1.427E-01	1	0	1.427E-01	N/A
Ra-226	Uranium	9.621E+00	4	2	2.405E+00	4.811E+00
Pb-210	Uranium	7.017E-01	0	2	N/A	3.509E-01
Po-210	Uranium	9.586E-02	1	0	9.586E-02	N/A
Th-232	Thorium	1.060E+00	1	0	1.060E+00	N/A
Ra-228	Thorium	6.282E+00	0	2	N/A	3.141E+00
Th-228	Thorium	7.393E+00	5	2	1.479E+00	3.697E+00
U-235	Actinium	7.009E-01	1	1	7.009E-01	7.009E-01
Pa-231	Actinium	1.712E+00	1	0	1.712E+00	N/A
Ac-227	Actinium	4.856E+00	5	3	9.712E-01	1.619E+00
Pu-241	Neptunium	9.749E-03	0	1	N/A	9.749E-03
Am-241	Neptunium	5.407E-01	1	0	5.407E-01	N/A
Np-237	Neptunium	1.552E+00	1	1	1.552E+00	1.552E+00
U-233	Neptunium	6.573E-02	1	0	6.573E-02	N/A
Th-229	Neptunium	2.328E+00	5	3	4.656E-01	7.760E-01

Appendix E: Analysis of Example Data

The data presented here include 23 soil samples from a deployment radiological sampling mission, 10 of which are samples on a post and 13 of which are off-post background samples. This soil was tested by gamma spectroscopy for 13 radionuclides. It was also tested in a proportional counter for gross alpha and beta activity. The data shown below is the activity measurements in pCi/g; the uncertainty and the minimum detectable concentration are not included.

Table E 1: Gamma Spectroscopy and Gross Alpha/Beta Activity from 23 Soil Samples

Sample #	Ac-228	Am-241	Bi-214	Co-57	Co-60	Cs-134	Cs-137
1	0.642	0	0.548	0	0	0	0.0316
2	0.637	0.0141	0.575	0.0121	0.00585	0.00045	0.166
3	0.730	0.0314	0.661	0.00145	0.015	0.0131	0.0853
4	0.598	0	0.662	0.0108	0.000808	0	0.179
5	0.449	0.00692	0.308	0.0067	0	0.00295	0
6	0.29	0	0.323	0.017	0.00749	0	0.022
7	0.347	0.235	0.875	0.151	0.00774	0	0.215
8	0.221	8.35	1.26	2.37	0.111	0	0
9	0.666	0.00318	0.615	0.00599	0.0104	0.00131	0.129
10	0.737	0	0.579	0	0.0216	0	0.0197
11	0.764	0	0.84	0.0129	0	0	0.0511
12	0.93	0.0116	0.631	0	0.00853	0.0145	0.0398
13	0.649	0	0.715	0.00691	0.00508	0	0.0197
14	0.726	0.0134	0.776	0	0.0136	0.0167	0.056
15	0.665	0.0151	0.58	0	0	0.0428	0.0167
16	0.633	0.0296	0.588	0.000731	0.0118	0.00776	0.0448
17	0.559	0.000946	0.6	0	0	0.00242	0.062
18	0.858	0	0.642	0	0.00031	0.0167	0.00947
19	0.798	0	0.491	0	0	0.0158	0.0202
20	0.909	0	0.688	0	0	0.0241	0.0466
21	0.88	0	0.559	0.00332	0	0	0.0342
22	0.741	0.018	0.637	0.0067	0	0.017	0.0586
23	0.887	0.00978	0.634	0	0	0	0.028

Sample #	Eu-152	Eu-154	Ir-192	Pa-234m	Th-234	U-235	Alpha	Beta
1	0	0.00173	0.0203	0	0.471	0.0604	9.90	8.84
2	0.0614	0.0204	0	0	0.234	0.128	8.28	14.80
3	0.0497	0	0	0.55	0.770	0.105	2.78	12.40
4	0.0448	0	0	1.55	0.976	0.108	6.18	12.50
5	0.0581	0.0299	0.0122	2.96	2.15	0.175	7.83	10.90
6	0	0	0.00157	0.347	0.0673	0.0777	8.41	7.95
7	0	0.0693	0.00454	367	255	16.2	435.00	352.00
8	0.0269	0.0871	0.0672	8470	5740	375	11300.00	8710.00
9	0.017	0.0128	0.00765	3.05	0.714	0.119	5.71	17.30
10	0.0326	0.0169	0.0349	4.32	0.719	0.113	9.46	12.50
11	0.00782	0.0172	0	1.92	0.395	0.12	16.50	13.90
12	0	0	0	2.99	0.421	0.0733	8.59	11.50
13	0.0639	0	0	3.72	0.314	0.11	14.50	10.40
14	0	0	0.0166	0	0.832	0.12	8.73	13.30
15	0	0	0.0127	0.0916	0.131	0.099	10.50	9.91
16	0	0.00154	0.0096	0.984	0.77	0.115	10.80	10.20
17	0	0	0	0	0.641	0.0883	7.80	8.69
18	0.0148	0.0305	0	0	0.456	0.128	5.82	12.10
19	0.0202	0	0	0.153	0.56	0.108	6.83	14.10
20	0	0.0614	0.00378	0	0.286	0.0798	10.60	12.40
21	0	0	0	3.55	0.709	0.0775	14.40	14.40
22	0	0	0.0128	0	0.476	0.116	7.85	12.80
23	0	0	0	0	0.519	0.0863	10.70	12.40

Using Equation 30 with factors used for a 0.05 rem/y (50 mrem/y) dose rate yields:

$$\frac{C_\alpha - 12.7}{20.8} + \frac{C_\beta - 20.1}{2.4} \leq 1$$

All of the samples easily passed the above condition besides two samples of interest: samples number 7 and 8. Therefore, all of the areas nearby the other 21 of these samples can be occupied, but further analysis and remediation is necessary in the areas of samples 7 and 8. For further optional analysis, refer to Equation 22:

$$\frac{C_{U\,Series}}{(C_{\lim})_{U\,Series}}+\frac{C_{Bi-214}}{(C_{\lim})_{Bi-214}}+\frac{C_{Ac-228}}{(C_{\lim})_{Ac-228}}+\frac{C_{U-235}}{(C_{\lim})_{U-235}}+\frac{C_{Co-57}}{(C_{\lim})_{Co-57}}\cdots$$

$$+\frac{C_{Co-60}}{(C_{\lim})_{Co-60}}+\frac{C_{Cs-134}}{(C_{\lim})_{Cs-134}}+\frac{C_{Cs-137}}{(C_{\lim})_{Cs-137}}+\frac{C_{Eu-152}}{(C_{\lim})_{Eu-152}}+\frac{C_{Eu-154}}{(C_{\lim})_{Eu-154}}\cdots$$

$$+\frac{C_{Ir-192}}{(C_{\lim})_{Ir-192}}+\frac{C_{Am-241}}{(C_{\lim})_{Am-241}}\leq 1$$

Again, all of the samples passed this condition except for samples 7 and 8. These samples exceed limits primarily because of the large amounts of natural uranium in these places, as indicated by the protactinium-234m, thorium-234, and uranium-235.

Also, an abnormally large amount of americium-241 is in sample 8. As stated earlier, the average worldwide concentration of americium-241 in the top 30 cm of soil is 0.0892 pCi/g (Agency for Toxic Substances and Disease Registry, 2004). The sample has 8.35 pCi/g of americium-241, which is almost 100 times that average. Also, this measurement exceeds its minimum detectable concentration, which is 1.73 pCi/g. Therefore, more investigation is necessary before the area surrounding this sample can be occupied. All of the rest of the samples in this set have americium-241 measurements below their reported MDC.

Appendix F: Applying Results to Examples of Natural Radionuclide Concentrations

A. IAEA Safety Reports Series No. 49 Recommendation

The International Atomic Energy Agency recommends concentrations of the Uranium Series, Thorium Series, and potassium-40 below which it is "unnecessary to regulate." (International Atomic Energy Agency, 2006) These concentrations are 1 Bq/g (27 pCi/g) for the Uranium Series and Thorium Series and 10 Bq/g (270 pCi/g) for potassium-40. These values are chosen since they are the "upper end of the worldwide distribution of activity concentrations in soil." (International Atomic Energy Agency, 2006)

Neglecting uranium-235 and assuming the 1.4 pCi/g for rubidium-87 (National Council on Radiation Protection & Measurements, 1987), the given concentrations of these radionuclides indicated the following alpha and beta emissions using Equations 23 and 24:

$$C_\alpha = [8 \times 27] + [6 \times 27] = 378$$

$$C_\beta = [6 \times 27] + [4 \times 27] + [0.893 \times 270] + [1 \times 1.4] = 512.51$$

Therefore, this limit implies 378 pCi$_\alpha$/g and 511 pCi$_\beta$/g. Applying Equation 30 and a 5 rem/y dose rate results in:

$$\frac{C_\alpha - C_{\alpha,bck}}{C_{\alpha,\lim}} + \frac{C_\beta - C_{\beta,bck}}{C_{\beta,\lim}} = \frac{378 - 12.7}{2079} + \frac{513 - 20.1}{241} = 2.22$$

This implies that the dose rate above background could be greater then 5 rem/y. Since the unity condition is equal to 2.22, it could be slightly over twice the 5 rem/y dose rate (or over 10 rem/y) if the dose came from the radionuclides with the highest dose rate per alpha/beta concentration.

This example is further proof that accurate background measurements are essential to using this methodology. If an area had background concentrations of 1 Bq/g for the Uranium Series and Thorium Series and 10 Bq/g for potassium-40, this method would show a possible dose rate of more than 10 rem/y over background (assuming worldwide average background) even if there was no contamination in the area.

B. Natural Radionuclide Sampling in Egypt

A study of natural radionuclides in Egypt yielded 30 samples, which were measured for concentration of the Uranium Series, the Thorium Series, and potassium-40. The samples indicate that there is “no radioactive hazard for human beings living in this region.” (El-Farrash, Yousef, Abu El-Ela, & El-Said, 1999)

One of these samples indicates a concentration of the Uranium Series and Thorium Series which is an order of magnitude higher than the other samples. This sample indicates 245.2 Bq/kg (6.62 pCi/g) of potassium-40, 412.1 Bq/kg (11.13 pCi/g) of the Uranium Series, and 422.2 Bq/kg (11.40 pCi/g) of the Thorium Series. Applying the same method used in Section A of this appendix and assuming 1.4 pCi/g of rubidium-87 implied that this sample indicates 157 pCi_{α}/g and 120 pCi_{β}/g. Applying Equation 30 and a 5 rem/y dose rate results in:

$$\frac{C_\alpha - C_{\alpha,bck}}{C_{\alpha,\lim}} + \frac{C_\beta - C_{\beta,bck}}{C_{\beta,\lim}} = \frac{157 - 12.7}{2079} + \frac{120 - 20.1}{241} = 0.48$$

Therefore, this sample passed the unity condition for a 5 rem/y dose rate limit. However, this sample did not pass this condition for a 50 mrem/y or 100 mrem/y dose rate limit.

A sample which is more typical of this set indicates 207.2 Bq/kg (5.59 pCi/g) of potassium-40, 17.4 Bq/kg (0.47 pCi/g) of the Uranium Series, and 12.4 Bq/kg (0.33 pCi/g) of the Thorium Series. This sample indicates 5.74 pCi_α/g and 12.0 pCi_β/g. Applying Equation 30 and a 50 mrem/y dose rate resulted in:

$$\frac{C_\alpha - C_{\alpha,bck}}{C_{\alpha,\lim}} + \frac{C_\beta - C_{\beta,bck}}{C_{\beta,\lim}} = \frac{5.74 - 12.7}{20.8} + \frac{12.0 - 20.1}{2.4} < 0$$

Since both of these fractions are less than zero, the alpha and beta emissions indicated a dose rate below the average worldwide background and therefore passed this condition.

Appendix G: Literature on Sampling, Surveying and Statistics

A. NCRP Report 129

In 1999, the National Council on Radiation Protection and Measurements (NCRP) issued a report titled “Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies” (National Council on Radiation Protection & Measurements, 1999). This report aimed to set limits on radionuclide concentrations of surface soils, which are defined to a depth of about 30 cm. The analysis only considered radionuclides whose half-lives are more than 30 days.

When defining these limits, they considered eight scenarios based on how the land was used and how it is populated. This is done such that different considerations are made for land used for agriculture, land used for residence, and land used for commercial purposes. For example, if land is used for agriculture, you need to consider the ingestion exposure to adults and children eating off this land, while considering the inhalation exposure to the adults who farm on this land. In the case of commercial land, you can consider only adults who work on this land and assume that nobody lives on this land.

B. HASL-300

The Environmental Measurements Laboratory (EML) is operated by the Department of Homeland Security. EML periodically release editions of the HASL-300 (Health and Safety Laboratory) report, which describe the methods and instruments used for environmental sampling at EML.

Several criteria are given for choosing an area to sample. The piece of land sampled needs to be undisturbed by industry during he period of interest. It needs to be a large, flat, open area such that there isn't much radionuclide movement on it. Also, the land should have good permeability such that the contamination is not diluted by runoff water. A grassy field is ideal for this.

This report gives details of how soil samples are collected and prepared for measurement at the EML. To use the "core method", they recommend 5 cm cores that are 8.9 cm in diameter and spaced 0.5 m apart. Additional soil is taken until a depth of 30 cm is reached. Ten of these samples are necessary to survey an area. This method prepares two depths to be analyzed: from the surface to 5 cm deep and from 5 cm deep to 30 cm deep.

The core method is the most used and recommended sampling procedure. The HASL-300 recommends various other methods for special scenarios. The "template method" is used where an area is too rocky to make use of the core method. The "trench method" is a way to establish a depth profile and see how the contamination varies in respect to depth. However, this method is too time and cost consuming to typically be feasible or practical.

C. NATO SIRA: Allied Engineering Publication 49

The North Atlantic Treaty Organization (NATO) published the NATO Handbook for Sampling and Identification of Radiological Agents (NATO SIRA). This handbook provides procedures and equipment requirements for sampling and identifying low-dose radiological sources in military operations other that nuclear war. Some scenarios included are areas with sealed sources,

radiological dispersion devices, depleted uranium, reactor fuel production, and nuclear facilities.

This information is presented in two volumes. The first volume is "Operational" and is a field guide for making decisions for radiological hazard scenarios and sampling in areas of operation. The second volume is "Forensic", which provides guidance on laboratory analysis of samples to identify radionuclides and provide dose estimates that can not be calculated and obtained in the areas of operation.

Volume 2 gives specific guidance on soil sampling methodology. In choosing a sight, the area needs to be undisturbed, unfertilized, away from roads and walkways, and consistently mowed such that the soil is fairly uncovered. Rocks and vegetation should be avoided. A coring tool with a diameter of 7.5 – 10 cm should be used. Ten or more samples should be taken for a total sampled area of 450 to 900 cm^2. Each of these samples should be taken the depth of 5 cm.

This guide provides three patterns to plot locations for these samples. The straight line pattern involves setting up a straight line that is 5 meters long and taking a sample every 50 cm. The box pattern directs setting up two 1 m^2 squares that are 3 m apart and sampling each corner and the center of these squares. The cross pattern directs setting up two crossing lines, one 5 m long and one 4 m long, and taking ten samples on these lines (each 1 m apart).

D. IAEA TECDOC 1092

The International Atomic Energy Agency (IAEA) has prepared a series of technical documents on how to respond to nuclear and radiological accidents. They published IAEA-TECDOC-1092, titled “Generic procedures for monitoring in a nuclear or radiological accident”, in 1999 to provide guidance on designing a program for emergency monitoring and sampling.

This text provides guidance on how to sample soil such that it can be evaluated for gamma/beta external dose and inhalation dose. This guide recommends that bare uncovered soil be collected to a constant depth defined before collecting. If the soil is covered by grass or weeds, they should be collected and sent as a vegetation sample to be analyzed separated. If snow covers the soil and the radionuclides are believed to be deposited after the snowfall, the snow should be sent as a separate sample.

E. TG-236A

In 2001, USACHPPM published a technical guide (TG) titled “Basic Radiological Dose Estimation – A Field Guide”. This guide was written to assess long-term health risks due to ionizing external radiation. It focuses on practical ways of doing this using minimal instrumentation and quick estimation methods.

This guide explains USACHPPM’s recommended method for sampling soil. It recommends soil be taken to a depth of 15 cm such that the sample weighs about 1 kg. Due to varying moisture and soil density, the diameter of this sample is variable.

This guide also provides guidance on site selection. It favors grassy areas with free from rocks or vegetation. If a sample includes pebbles or stones larger than 2.5 cm in diameter, they should not be used.

F. TG-251

This technical guide, which USACHPPM released as a draft in 2001, is titled an "A Soldier's Guide to Environmental and Occupational Field Sampling for Military Deployment". This guide is a concise reference for planning and executing soil, water, air, and surface wipe surveys in deployment situations.

TG-251 gives guidance on statistical methods for determining the number of samples needed for acceptable precision of the measurement. This methodology is detailed in the EPA document "Soil Sampling Quality Assurance User's Guide".

G. Soil Sampling Quality Assurance User's Guide

The statistical guidance for quantity of soil samples provided by TG-251 is primarily from "Soil Sampling Quality Assurance User's Guide", a 1989 EPA publication. This guide separates area surveys into three purposes: preliminary site investigation, emergency cleanup, and planned removal and remedial response.

Preliminary site investigation is defined to be the "foundation upon which other studies in hazardous waste site assessments should be based." (Environmental Protection Agency, 1989) This type of survey is done to determine if the conditions cause enough potential damage to human health to warrant emergency action and to determine if the long-term risk of health

hazards is acceptable. If soils meet the set criteria, no further attention will be given to them.

For these investigations, a confidence level of 70-80% is recommended, which implies a 20-30% chance of a Type I error. The chance of a Type I error is called alpha (α). This error refers to the chance of a false positive; in reference to soil sampling, this is the chance of measuring a higher concentration of radionuclides in the soil than the acceptable levels when these concentrations are actually below acceptable limits.

A power of 90-95% is recommended, which implies a 5-10% chance of a Type II error. The chance of a Type II error is called beta (β). This error refers to the chance of a false negative; in reference to soil sampling, this is the chance of measuring a lower concentration of radionuclides in the soil than the acceptable levels when these concentrations are actually above acceptable limits. Type II errors are considered to be more important than Type I errors for preliminary site investigations.

The other parameter used to determine soil sample quantity is the relative increase over background to be detectable with a probability of (1-β) (also referred to as the "minimum detectable relative difference"). This increase is shown as:

$$relativeincrease = \frac{100(\mu - \mu_B)}{\mu_B} \tag{34}$$

μ is the measured mean concentration and μ_B is the mean background concentration. The recommended relative increase for preliminary site investigation is 10-30%.

For a one-sided one-sample t-test, the number of samples (n) to achieve a given confidence level and power at a given minimum detectable relative difference is:

$$n \geq \left[\frac{Z_\alpha + Z_\beta}{D} \right]^2 + 0.5 Z_\alpha^2 \tag{35}$$

Z_α and Z_β are the percentile of the standard normal distribution such that $P(Z \geq Z_a)$ and $P(Z \geq Z_b)$, respectfully. This test uses an infinite number of degrees of freedom (since we do not yet know the number of samples), so the t-distribution becomes a normal distribution. The variable D represents the relative increase divided by the coefficient of variation, which is the standard deviation (σ) divided by the mean value of the measurement (x). Therefore, the equation for D becomes:

$$D = \frac{relativeincrease}{\frac{\sigma}{x}} \tag{36}$$

The number of samples (n) should be rounded up to the nearest integer.

H. MARSSIM

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) were assembled by four major contributors: the Department of

Defense (DOD), the Department of Energy (DOE), the Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NRC). This guide provides information on how to perform and evaluate surface soil and building surface surveys for radiological contamination for final status surveys after any necessary remedial actions.

The soil being analyzed will be compared to a derived concentration guideline level (DCGL). A DCGL is a radionuclide-specific concentration that results in a dose high enough to trigger further investigation or intervention.

If residual radioactivity is spread over the area of concern evenly, the $DCGL_W$ is used. The "W" refers to the Wilcoxon Rank Sum test, which is the test used to show compliance if the radionuclide of interest is present in background. If the radionuclide of interest is not present in background, the Sign test is used, although the $DCGL_W$ is still used. If a small area within the area of concern has elevated radioactivity, a $DCGL_{EMC}$ is calculated for that small area. The "EMC" refers to elevated measurement comparison. Since choosing a statistical depends on whether or not radionuclides of interest are in the background, it is necessary to have background samples. This means there need to be samples from a nearby area that is undisturbed by industry or residence, but is similar in density, slope (for comparable runoff), and composition (in amount of rocks or tree roots).

The null hypothesis of the statistical tests in MARSSIM is the median concentration of residual radioactivity in the given area is greater than the DCGL (Department Of Defense et al., 2000). If all of the measurements taken are less

than the DCGL, no further testing is necessary and the null hypothesis is rejected, assuming the radionuclides of concern do not appear in the background. If the average of these measurements exceeds DCGL, the criteria of the test are not met and further investigation or measurement is necessary beyond soil sampling. If the average of the measurements is below the DCGL but one or more of the measurements exceeds the DCGL, it is necessary to conduct statistical sign tests and compare elevated areas.

One of the assumptions made for the statistical tests used in MARSSIM is that the radioactivity concentration is uniform across the entire area considered. A method used to analyze this is a posting plot, which is a map showing where the measurements were made with the value of each measurement written on its location. This allows for easy identification of elevated radioactivity in a small area.

A MARSSIM survey uses histograms to determine the validity of a Gaussian assumption. A histogram divides the measurements into small ranges and shows the frequency of measuring in each range. By seeing the distribution of the data, it is possible to know whether or not a Gaussian assumption is reasonable for a particular data set.

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